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EXPERIMENTAL AND THEORETICAL STUDIES OF AREA SUCTION
FOR THE CONTROL OF THE LAMINAR BOUNDARY LAYER
ON A POROUS BRONZE NACA 64A010 AIRFOIL

By Dale L. Burrows, Albert L. Braslow, and Neal Tetervin

Langley Aeronautical Laboratory
Langley Air Force Base, Va.



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SUMMARY

A low-turbulence wind-tunnel investigation was made of an NACA 64A010 airfoil having a porous surface of sintered bronze to determine the reduction in section drag coefficient that might be obtained at large Reynolds numbers by the use of suction to produce continuous inflow through the surface of the model (area suction). In addition to the experimental investigation, a related theoretical analysis was made to provide a basis of comparison for the test results.

Combined wake and suction drags lower than the drag of the plain airfoil and virtually full-chord laminar flow were obtained up to a Reynolds number of approximately 8.0×10^6 for a porous airfoil having surfaces that were neither aerodynamically smooth nor fair. The experimental results indicated the possibility of extending the low-drag characteristics to larger Reynolds numbers by means of a more uniform chordwise distribution of suction inflow. Although stabilizing action of area suction was manifest, some of the results might be interpreted to mean that surface protuberances had adverse effects on the laminar stability. The data obtained thus far are not believed to be of sufficient scope to determine whether area suction for the control of the laminar boundary layer can be made practical.

INTRODUCTION

A preliminary investigation of an NACA 64A010 airfoil model with a porous blotting-paper surface (reference 1) indicated that area suction had a stabilizing effect on the laminar boundary layer. The stabilizing effect was noticed up to a Reynolds number of 6×10^6 in spite of a wavy flexible surface.

In the belief that a smoother and less flexible porous surface would provide more reliable drag data and boundary-layer-stability indications,

an experimental investigation is being made in the Langley two-dimensional low-turbulence pressure tunnel of an airfoil model of NACA 64A010 profile that has a porous sintered-bronze surface. Results are presented herein of the initial tests which were made with an airfoil having a bronze skin of high porosity up to a Reynolds number of approximately 17×10^6 and with suction-flow coefficients up to approximately 0.01. Wake-drag coefficients, suction losses, and boundary-layer velocity profiles were measured.

In order to provide a basis of comparison for the measured suction flows, the stability of the laminar boundary layer was calculated for two important cases of chordwise suction distribution for the test airfoil. Theoretical results are also presented for a flat plate with uniform suction. The calculations were made by combining Schlichting's theory for the computation of the laminar boundary layer (reference 2) with Lin's theory for the determination of the stability of the laminar velocity profile (reference 3). Suction quantities necessary to keep the boundary layer neutrally stable at all points along the airfoil chord were calculated for Reynolds numbers of 6×10^6 , 15×10^6 , and 25×10^6 . The minimum suction quantities required to keep the boundary layer stable were obtained also for the case where the inflow velocity is constant over the entire surface.

SYMBOLS

α_0	section angle of attack
c	airfoil chord
b	span of porous surface
x	distance along chord from leading edge of airfoil
s	distance along surface from leading edge of airfoil
y	distance normal to surface of airfoil
ρ	free-stream mass density
U_0	free-stream velocity
q_0	free-stream dynamic pressure $\left(\frac{1}{2} \rho U_0^2 \right)$

U	local velocity parallel to surface at outer edge of boundary layer
u	local velocity parallel to surface and inside boundary layer
Q	total quantity rate of flow through both airfoil surfaces
C_Q	suction-flow coefficient $\left(\frac{Q}{bcU_Q}\right)$
H_0	free-stream total pressure
H_1	total pressure in model interior
p	local static pressure on airfoil surface
S	airfoil pressure coefficient $\left(\frac{H_0 - p}{q_0}\right)$
R	free-stream Reynolds number based on airfoil chord
C_P	suction-air pressure-loss coefficient $\left(\frac{H_0 - H_1}{q_0}\right)$
c_{d_w}	section wake-drag coefficient
c_{d_s}	section suction-drag coefficient $(C_Q C_P)$
c_{d_T}	section total-drag coefficient $(c_{d_s} + c_{d_w})$
δ^*	displacement thickness $\left(\int_0^\infty \left(1 - \frac{u}{U}\right) dy\right)$
θ	momentum thickness $\left(\int_0^\infty \frac{u}{U} \left(1 - \frac{u}{U}\right) dy\right)$
$R_{\delta^*} = \frac{U\delta^*}{\nu}$	
ν	kinematic viscosity

v_o velocity through airfoil surface (for suction, $v_o < 0$;
for blowing, $v_o > 0$)

Δp static pressure drop across porous surface

c_{v_o} porosity factor $\left(\left| \frac{v_o}{\Delta p} \right| \mu t \right)$

μ absolute viscosity

t thickness of porous material

$$z = \left(\frac{\theta}{c} \right)^2 \frac{U_o c}{v} \quad (\text{reference 2})$$

G function of k and k_1 (reference 2)

$$k = z \frac{d \frac{U}{U_o}}{d \frac{s}{c}} \quad (\text{reference 2})$$

$$k_1 = f_1 \sqrt{z} \quad (\text{reference 2})$$

$$f_1 = \frac{-v_o}{U_o} \sqrt{\frac{U_o c}{v}} \quad (\text{reference 2})$$

K profile shape parameter (reference 2)

$$\eta = \frac{y}{\delta_1} \quad (\text{reference 2})$$

δ_1 measure of boundary-layer thickness (reference 2)

u_c velocity of disturbance in boundary layer

$R_{\delta^* \text{crit}}$ value of R_{δ^*} at which disturbance is neither damped nor amplified

MODEL

Photographs of the 3-foot-chord by 3-foot-span model mounted in the Langley two-dimensional low-turbulence pressure tunnel are presented as figure 1. The model was formed to the NACA 64A010 profile, ordinates for which are presented in reference 4. The theoretical pressure distribution of this airfoil at zero angle of attack is presented in figure 2.

A sketch showing details of the model construction is presented in figure 3. The upper and lower surfaces for a 13-inch center section of the span were constructed from a continuous sheet of porous sintered bronze with a single spanwise joint at the model trailing edge. The model was constructed with two hollow cast-aluminum end sections which were machined to contour and connected to an under-contour hollow center casting that served as a base support for the bronze skin. The skin was directly supported on a chordwise arrangement of $\frac{1}{4}$ -inch spanwise rods which were attached to the under-contour casting. The chordwise locations of these rods are shown in figure 4. This arrangement of support rods, in which the rods made essentially line contact with the skin, was intended to provide as much open area as possible on the inner side of the skin so that very little of the skin would be blanked off from the suction flow. The skin was of 13-inch span and was fastened only at the spanwise edges to $\frac{1}{2}$ -inch inner end plates; consequently a 12-inch span of skin was left open to suction. The center casting was perforated with 1-inch holes over the center portion and 1-inch slits at the model leading and trailing edges to provide a passageway for the air from the skin into the inner chamber of the hollow casting. A photograph which shows the model with the porous skin removed is presented as figure 5.

The sintered bronze sheet was fabricated of spherical bronze powder that was specified to be small enough to pass through a 200 mesh screen but too large to pass through a 400 mesh screen. The thickness of the sheet was found to vary about ± 0.010 inch from a mean of 0.080 inch.

As a result of a low modulus of elasticity of the material and the variations in thickness, the airfoil contour as tested was quite wavy. Absolute variations from the true profile were not measured; however, a relative waviness survey was made at various spanwise stations with a three-point indicating mechanism (fig. 6). An estimate of the degree of waviness of the bronze surface may be obtained by comparing the profiles for the bronze surface with the profiles of the cast-aluminum end sections; the profiles of the end sections varied no more than ± 0.003 inch from the true airfoil profile.

The porosity of the sintered-bronze material was such that the flow quantity varied directly with the pressure drop, as is characteristic of dense filters. With air at standard conditions the measured porosity of the skin mounted on the model was such that an applied suction of 0.12 pound per square inch induced a velocity of 1.0 foot per second through the material; these values amount to a porosity factor c_{v_0}

equal to 1.44×10^{-10} square foot which is independent of the material thickness and the viscosity and density of the flow medium provided that the flow through the material is purely viscous. The outer surface of the skin was sanded to reduce local surface irregularities with a resultant decrease in porosity at local points because of a "smearing over" of metal particles. Frequent vacuum cleaning of the surface eliminated large changes in the porosity with time because of dust clog.

Photomicrographs of the sanded skin are presented as figure 7 to give a visual indication of the porosity. Figure 7(a) is representative of about 80 percent of the sanded surface. Figures 7(b) and 7(c) indicate the amount by which the metal was smeared as a result of excessive sanding on poorly sintered areas. Porosity measurements made after sanding, however, indicated that the average porosity for the whole airfoil was not affected appreciably by the sanding operation.

The model was made such that the chordwise inflow could be altered by installing orifices in the model base casting as shown in figure 4. Flow between compartments formed by the $\frac{1}{4}$ -inch rods could be prevented by sealing the rods to the skin with rubber cement. The model arrangement with orifices and compartment seal is referred to in this paper as the compartmented model, whereas without the orifices and seal the model is called the uncompartmented model. In order to prevent outflow from the upper and lower leading-edge compartments, the leading-edge skin for the compartmented model was saturated with lacquer for a distance of 1 inch ($\frac{s}{c} = 0.028$) from the leading edge on both upper and lower surfaces as shown in figure 4.

APPARATUS AND TESTS

The model was tested in the Langley two-dimensional low-turbulence pressure tunnel and was mounted as shown in figure 1. A detailed description of this tunnel is given in reference 5. Flow measurements for the suction air were made by means of an orifice plate in the suction duct. The suction flow was taken through one of the model end plates and was regulated by varying the blower speed and the diameter of the orifice which was used to measure suction flow.

A static tube was used to measure the suction pressure in the inner compartment of the center casting. Since the velocity was low, the measured static pressure could be taken as the total pressure. These data were used to obtain the total pressure lost by the suction air in passing from the free stream to the inner chamber of the model and were also used to give an indication of outflow which occurred when the pressure inside the model was greater than the lowest pressure on the airfoil surface. A conventional multitube pressure "mouse" (reference 6) was used to obtain the boundary-layer measurements. All wake drags were measured with a survey rake located at about 70 percent of the chord behind the model trailing edge.

The skin was the only resistance to the suction for the first part of the tests (uncompartmented model); that is, air passages between the skin and the inner chamber were large enough to make the internal losses low in comparison with the pressure drop through the skin. For this model arrangement, suction pressures and center-line wake drags were measured for Reynolds numbers of 3.0×10^6 , 5.9×10^6 , 9.0×10^6 , 12.0×10^6 , and 16.7×10^6 and for suction-flow coefficients up to 0.01. Boundary-layer measurements were made on the upper surface at 83 percent chord for the same range of Reynolds numbers and flow coefficients as for the drag measurements. Station 0.83c was the most rearward position at which the mouse could be mounted conveniently. Spanwise wake-drag surveys were made at a Reynolds number of 3.0×10^6 for suction-flow coefficients up to 0.0079 and at a Reynolds number of 6.0×10^6 for suction-flow coefficients up to 0.0048.

For the second part of the tests (compartmented model), wake-drag surveys were made at Reynolds numbers of 3.0×10^6 , 5.9×10^6 , 7.6×10^6 , 7.8×10^6 , and 9.1×10^6 for suction-flow coefficients up to 0.004. The use of flow-control orifices in each compartment of this model had the disadvantage that any one set of orifices such as shown in figure 4 was able to produce a near-uniform chordwise inflow distribution only at free-stream Reynolds numbers below the design value, which for this case was about 6.0×10^6 . No attempt was made to measure the flow in each compartment because of the exploratory nature of the tests; only total suction flows were measured. Total suction pressures were measured at a point inside the hollow-center casting by the same method as for the first model condition. The suction pressure was also measured in compartment 5 under the upper-surface skin (fig. 4) to obtain an indication of outflow through the skin; calculations indicated that compartment 5, because of the peculiarities of the throttling system, would be the most critical to outflow.

RESULTS AND DISCUSSION

Uncompartmented Model

Wake drag.— The variation of section wake-drag coefficient with suction-flow coefficient is shown in figure 8(a) for Reynolds numbers up to 16.7×10^6 for the uncompartmented model. The wake drags presented are for zero angle of attack. Wake drags measured at the model center line are presented because they were found to be representative of the uniform drags measured over the portion of the span of the model that was unaffected by the juncture between the bronze skin and the solid end sections. The static pressure in the interior of this model arrangement was everywhere the same.

At a Reynolds number of 3.0×10^6 the section wake-drag coefficient for $C_Q > 0.0028$ was constant and equal to about 0.0008. For a Reynolds number of 5.9×10^6 and for $C_Q > 0.0050$ the wake-drag coefficient remained practically constant at 0.0005. The wake drag at Reynolds numbers of 9.0×10^6 , 12.0×10^6 , and 16.7×10^6 , however, decreased steadily with increase in C_Q but never became less than the lowest drags obtained at a Reynolds number of 5.9×10^6 , even for a suction-flow coefficient as high as 0.010.

The rapid increase of c_{d_w} that occurred with decreasing C_Q for values of C_Q slightly less than 0.0024 at a Reynolds number of 3.0×10^6 and for values of C_Q less than about 0.0048 at a Reynolds number of 5.9×10^6 was caused by a rapid forward shift of the point of transition from laminar to turbulent flow. The curves in figure 9 show that at 83 percent of the chord, at a Reynolds number of 6.0×10^6 , the boundary layer on the upper surface was laminar for a C_Q of 0.0048 but was turbulent for only a slightly lower C_Q of 0.0046. Other boundary-layer surveys, not presented herein, indicated that, whenever a rapid increase in drag coefficient accompanied a small decrease in flow coefficient, the boundary layer changed rapidly from laminar to turbulent over a large portion of the surface.

Outflow through the surface occurred when the static pressure inside the skin was greater than the minimum static pressure on the outside of the airfoil. The curves of c_{d_w} against C_Q are shown in figure 8(a) as dash lines when outflow occurred locally and as solid lines when inflow

occurred over the whole airfoil. At Reynolds numbers of 3.0×10^6 and 5.9×10^6 the values of minimum C_Q required to prevent outflow are seen to be very near the value of C_Q at which the drag changes rapidly. It seems probable that outflow produced the rapid forward shift of the transition point at least for Reynolds numbers up to 5.9×10^6 . From the plots of c_{d_w} against C_Q the lowest C_Q for which no outflow occurred at each Reynolds number is seen to increase with increasing Reynolds number. This increase of the minimum value of C_Q with Reynolds number is a result of the linear variation of flow velocity through the sintered bronze with pressure drop across the surface; the minimum C_Q for no outflow increases with the free-stream Reynolds number. A more detailed treatment of this subject is presented in appendix A.

Wake-drag measurements for Reynolds numbers of 9.0×10^6 , 12.0×10^6 , and 16.7×10^6 as shown in figure 8(a) indicated that laminar flow was probably not maintained over the complete chord of the model. The gradual decrease of wake-drag coefficient with increasing flow coefficient may have been caused by either a gradual rearward movement of the transition point with increasing flow coefficient or by a mere reduction in the size of the turbulent boundary layer. The extreme thinness of the boundary layer at these high Reynolds numbers prevented an accurate determination of its shape even near the trailing edge. It should be noted that full-chord laminar flow was not maintained even though the suction pressures were sufficient to prevent outflow. Theoretical calculations for a Reynolds number of 16.7×10^6 for the configuration and inflow distribution tested indicated that the laminar boundary layer should have been very stable.

The basis for a possible explanation of the transition difficulties at the higher Reynolds number is indicated in reference 7. It is shown therein that the presence of a surface projection will cause premature transition of a laminar boundary layer when the Reynolds number based on the height of the projection and the velocity at the top of the projection exceeds a critical value that is dependent on the geometry of the projection.

Although the numerous protuberances on the bronze skin were sanded to very small dimensions, calculations indicated that the relatively large amount of suction near the leading edge of the model so thinned the boundary layer (especially at the higher Reynolds numbers) that even the particles forming the material probably projected completely through the boundary layer. Because of the high velocity at the top of the particles at the high Reynolds numbers, it seems entirely possible that the critical Reynolds number for the roughness was exceeded in spite of its

small height, and thus large disturbances were introduced into the boundary-layer flow. The relatively high drag coefficients measured under such conditions of roughness show that the suction-type profile is not stable to sufficiently large disturbances. The relative stability of the suction and no-suction type profiles to finite disturbances is an important problem for future research.

The difficulties associated with obtaining low drag at high values of the Reynolds number are seen from the foregoing discussion to result from nonuniformity of the chordwise inflow distribution (excessive suction near leading edge) and from the surface irregularities of the material. If the Reynolds number is increased by increasing the value of U_0/V while the size of the model is held constant, the inflow distribution becomes increasingly nonuniform (see equation (A4), appendix A) and the ratio of the size of the roughness to the boundary-layer thickness increases. Both of these effects are unfavorable for obtaining low drag at high Reynolds numbers. On the other hand, if c_{v0}/t is held constant (no change in the type of material used) and the Reynolds number is increased by increasing the chord of the model, the inflow distribution will remain unchanged but the ratio of the size of the roughness to the boundary-layer thickness will vary inversely as the square root of the Reynolds number. For this reason, it seems likely that favorable results can be obtained more easily with a large model than with a small one.

Total drag.— The measured pressure-loss coefficient for the suction air was used to calculate the section suction-drag coefficient and the results are shown in figure 8(b). The suction-drag coefficient based on the model chord was calculated as $C_p \times C_Q$, which is the drag equivalent of the power required to pump the suction air back to free-stream total pressure. (See appendix B.) In this method of calculating suction drag, the over-all pumping efficiency is considered to be equal to that of the main propulsive system.

As may be seen in figure 8(b), the variation of c_{ds} was assumed to be linear with C_Q for all Reynolds numbers because of the small variation in C_p , which averaged about 1.32. Inasmuch as there is no induced drag on a two-dimensional model, the total drag is the sum of the suction and wake drags. As shown in figure 8(b), the minimum total drag at a Reynolds number of 3.0×10^6 occurred at a C_Q of about 0.0024, which was slightly less than the minimum C_Q required to prevent outflow; the minimum total-drag coefficient of 0.0042 is a slight improvement over 0.0044, the drag coefficient of a solid NACA 64A010 airfoil with a smooth and faired surface at a Reynolds number of 3.0×10^6 (shown in figure 8(b) as taken from reference 4). The porous model, however, did not have a completely smooth and faired surface, and a test made with the surface sealed resulted in a no-suction-drag coefficient of approximately 0.0052. The value of 0.0052

is probably somewhat low inasmuch as the surface was sealed with external applications of water glass and wax; as a result, the surface texture was unavoidably improved over that for the unsealed condition although the waviness of the surface was probably not affected. The no-suction-drag coefficient, therefore, would probably be somewhat greater than 0.0052 but less than 0.0092, the value for the extreme condition of standard leading-edge roughness on the solid airfoil (reference 4). The minimum total-drag coefficient increased with increasing Reynolds number with the result that, at a Reynolds number only slightly greater than 3.0×10^6 , no decrease in total drag was obtained by suction. A large proportion of the total drag consisted of suction drag because of the excessive amounts of air required at the leading-edge and trailing-edge surfaces of the airfoil in order to prevent outflow at the minimum pressure point.

The total amount of air that needs to be withdrawn in order to prevent outflow can be greatly reduced by applying suction separately to small portions of the airfoil surface. This purpose was accomplished by dividing the underskin region into separate compartments as described previously in the section entitled "Model."

Compartmented Model

Wake drag.— Wake-drag tests made on the compartmented model previous to the tests reported herein indicated that the nose should be sealed for about 1 inch back from the leading edge (fig. 4) in order to obtain low drags at reasonable suction coefficients. The character of the flow at the leading edge before the nose was sealed was not clearly established, but early transition probably occurred because of excessive local outflow near the nose where the external-pressure variation over the first compartment was very large. A better understanding of these outflow difficulties may be gained from the discussion on compartmentation in appendix A.

As shown in figure 10(a), the section wake-drag coefficient for the model with sealed nose and compartments was less than 0.0010 (for Reynolds numbers as high as 7.8×10^6) for suction-flow coefficients that ranged from 0.0015 at a Reynolds number of 3.0×10^6 to about 0.0035 at a Reynolds number of 7.8×10^6 . At a Reynolds number of 9.1×10^6 the wake drag remained greater than 0.0030 even for flow coefficients as high as 0.0040. Failure to obtain lower wake drags was believed to result from the presence of outflow. Although no outflow and low wake drags might have been obtained at higher suction-flow coefficients, the total drag would not have been reduced because of the excessive suction drags that would have resulted from the large suction quantities.

A comparison of figures 8(a) and 10(a) indicates that for equal Reynolds numbers the minimum suction-flow coefficients for which low wake drags were obtained for the compartmented model were about one-third of

those required for the uncompartmented model. The largest Reynolds number at which low drag occurred was also extended by compartmenting the model. Thus, low wake drags might be obtained at Reynolds numbers higher than 7.8×10^6 and at suction-flow coefficients lower than 0.0035 if the chordwise distribution of suction were further controlled.

Total drag.— Throughout the low-drag range the average total pressure loss in the suction air for the compartmented model corresponded to an average pressure-loss coefficient of about 1.40. This average loss coefficient was used to compute the suction-drag coefficient that could be expected for an airfoil compartmented in the same manner as the model tested. The sum of the wake and suction drags is shown in figure 10(b).

At Reynolds numbers of 3.0×10^6 and 5.9×10^6 the minimum c_{dT} was about 0.0028. At higher Reynolds numbers the minimum c_{dT} was larger because of the larger C_Q necessary for low wake drags. In spite of the larger C_Q at a Reynolds number of 7.8×10^6 , the minimum total-drag coefficient, 0.0048, was only slightly greater than the drag coefficient for the smooth solid-surface model of the same contour (reference 4) and somewhat less than the drag coefficient for the porous bronze model with the skin entirely sealed to suction.

The over-all gain in compartmenting the model may be seen by comparing the total drags in figures 8(b) and 10(b) from which it is seen that at a Reynolds number of 5.9×10^6 the total drag of the compartmented model was only 40 percent of that for the uncompartmented model.

Observations on Stability of Laminar Boundary Layer

In addition to the indication of the stabilizing effect of area suction that was obtained from the wake drags, a further indication of the stabilizing action of area suction was noted during a few spanwise wake surveys made near the junctures between the porous center skin and the solid end castings. Turbulent flow emanating from these junctures was found to limit the spanwise extent of low drag measured in the wake behind the model trailing edge. Figure 11 shows that an increase in the suction-flow coefficient increased the spanwise extent of low wake-drag coefficients at the center portion of the model. This result seems to indicate that area suction reduced the angular spread of turbulence downstream of a disturbance.

For the compartmented configuration the boundary layer was found to remain stable in the presence of some local outflow; this effect may be seen in figure 10(a) in which the outflow portions of the wake-drag curves (dash lines) extend into the low drag range, at least for Reynolds numbers

of 5.9×10^6 , 7.6×10^6 , and 7.8×10^6 . The range of suction-flow coefficient for outflow shown in figure 10(a), however, may not be entirely reliable inasmuch as the theoretical rather than an experimental external-pressure distribution was used for determination of outflow conditions.

Indications of adverse effects of surface protuberances on the stability of the laminar boundary layer with suction were obtained at low Reynolds numbers during a preliminary test run of the uncompartmented model before the model surfaces were sanded. For this condition, numerous protuberances existed of sufficient magnitude to cause premature transition of the boundary layer at a Reynolds number as low as 3.0×10^6 . It is possible, however, that the excessive suction at and near the model leading edge may have unduly decreased the boundary-layer thickness relative to the size of the projections, thus the sensitivity of the boundary layer to the existing disturbances was unnecessarily increased. This explanation, as discussed previously, was prompted by the work of reference 7. Although surface roughness did not appear to cause transition on the sealed-nose compartmented model for the combinations of Reynolds numbers and flow rates that were tested, it is believed that with other combinations of Reynolds numbers and suction rates (at least for the same model) the boundary layer could become thin enough to allow the surface roughness to cause transition. More information on the effects of area suction on the stability of the laminar boundary layer in the presence of surface disturbances is still required before it can be determined whether area suction can be made practical for the control of the laminar boundary layer.

Theoretical Calculations

In order to provide a standard of comparison for the experimental results, the characteristics of the laminar boundary layer were calculated for flow into the surface of the NACA 64A010 airfoil at an angle of attack of 0° . The minimum suction quantities necessary to keep the laminar boundary layer neutrally stable over the entire surface at Reynolds numbers of 6×10^6 , 15×10^6 , and 25×10^6 were computed. The stability of the boundary layer was also investigated for cases in which the velocity through the surface was everywhere the same.

The boundary-layer velocity profiles and thicknesses were calculated by the Schlichting method (reference 2), an approximate method. The velocity profiles of the Schlichting method are a single-parameter family of curves for which the parameter depends on the velocity of flow into the surface, the pressure gradient along the surface, the boundary-layer thickness, and the kinematic viscosity of the fluid. The single-parameter family of velocity profiles is used with the boundary-layer momentum equation to obtain a first-order differential equation. In the calculations, the differential equation of reference 2 was integrated by Euler's step-by-step method. In the process of integrating the differential equation, the boundary-layer profiles and boundary-layer thicknesses are found at each point along the wing surface. The lengths of the steps in the integration process were about the same for all the calculations and were so small that halving them made no important difference for the no-suction case and a Reynolds number of 25×10^6 .

In order to begin the calculation, the value of $\frac{dz}{ds}$, the rate of change of a representative boundary-layer thickness parameter, at $x = 0$ (reference 2) was taken as zero. This value of $\frac{dz}{ds}$ was found from the equation

$$\left(\frac{dz}{ds/c}\right)_{\frac{s}{c}=0} = \frac{\left[z \left(\frac{d^2U/U_0}{ds/c^2} \right) \frac{\partial G}{\partial k} + \frac{df_1}{ds/c} \sqrt{z} \frac{\partial G}{\partial k_1} \right]}{\left[\frac{dU/U_0}{ds/c} \left(1 - \frac{\partial G}{\partial k} \right) - \frac{f_1}{2} \frac{\partial G}{\partial k_1} \frac{1}{\sqrt{z}} \right]}_{\frac{s}{c}=0}$$

which was obtained by applying L'Hospital's Rule to the equation for $\frac{dz}{ds/c}$, equation (30) of reference 2. In order to continue the calculations as far as the trailing edge of the airfoil, it was necessary to modify slightly the Schlichting method by extrapolation of the curves in figures 5 and 6 of reference 2 beyond the value of k for which the Schlichting method breaks down. The recommendation of reference 2 that separation be assumed to exist when k equals -0.0682 was ignored in order to avoid the contradiction that the boundary-layer profile can become more convex and, at the same time, approach separation.

Lin's approximate formula (reference 3) was used to calculate the Reynolds number $R_{\delta^* \text{ crit}}$ at which any Schlichting velocity profile is neutrally stable. The stability theory as originally derived assumed that the boundary-layer thickness and velocity distribution did not vary with distance along the surface. Pretsch (reference 8) showed that the rates of variations in the thickness and velocity distribution which normally occur can have only a second-order effect on the stability. Lin's stability theory may be used, therefore, to calculate the stability of boundary layers in the presence of pressure gradients. When combined with the Schlichting method, Lin's formula becomes

$$R_{\delta^* \text{ crit}} = \frac{\left[1 - K \left(2 - \frac{6}{\pi} \right) \right] 25 \left(\frac{du/U}{d\eta} \right)_1}{u_c^4}$$

where u_c is equal to the value of u for which

$$-\pi \left(\frac{du}{d\eta} \right)_1 \left[3 - \frac{2 \left(\frac{du}{d\eta} \right)_1 \eta}{u/U} \right] \frac{u/U \left(\frac{d^2 u}{d\eta^2} \right)}{\left(\frac{du}{d\eta} \right)_1^3} = 0.58$$

and where the subscript 1 denotes "at surface." The application of Lin's formula to the Schlichting profiles results in the curve of figure 12 which shows the variation of the critical Reynolds number $R_{\delta^* \text{crit}}$ with change in the Schlichting velocity profile shape parameter K . In figure 13 are shown velocity profiles for three values of K .

A special procedure was used to calculate the distribution of the velocity of flow through the surface that was necessary to keep the boundary layer neutrally stable, R_{δ^*} equal to $R_{\delta^* \text{crit}}$. For these cases, suction was begun at the first station at which the boundary layer would become unstable without suction. The special method depends on the fact that the condition of neutral stability, $R_{\delta^* \text{crit}} = R_{\delta^*}$, can be written as

$$R_{\delta^* \text{crit}} = \frac{U}{U_0} \sqrt{z} \sqrt{R} \frac{\delta^*}{\theta}$$

or

$$\frac{R_{\delta^* \text{crit}}}{\delta^*/\theta} = \phi(K) = \frac{U}{U_0} \sqrt{z} \sqrt{R}$$

where $R_{\delta^* \text{crit}}$, $\frac{\delta^*}{\theta}$, and ϕ are functions only of K . The numerical value of the function $\phi(K)$ depends only on $\frac{U}{U_0} \sqrt{z} \sqrt{R}$. With a known value of z at the station at which suction begins, K can be found from the value of $\frac{U}{U_0} \sqrt{z} \sqrt{R}$. All the quantities necessary to proceed to the next station by the step-by-step integration process can be calculated once K is determined. The calculation of these quantities provides the value of the local suction velocity ratio v_0/U_0 .

In figure 14 are presented the curves of R_{δ}^* and $R_{\delta}^*_{crit}$ as determined from the calculation for the suction flow required to keep the boundary layer neutrally stable at all points on the airfoil at a Reynolds number of 15×10^6 . The calculated variation of v_o/U_o over one surface is shown in figure 15. The suction flow required to keep the boundary layer neutrally stable decreases slowly as the region of falling pressure on the airfoil surface is traversed. When the region of rising pressure is entered, the required suction rises rapidly and continues to increase to the trailing edge. The summary of the results of the computations for the minimum suction quantities is presented in figure 16.

In figure 17 are presented curves of $R_{\delta}^*_{crit}$ and R_{δ}^* for cases where v_o/U_o is the same over the entire surface. The figures illustrate that by a sufficient increase in the value of the suction parameter $\frac{v_o}{U_o} \sqrt{R}$ the position at which the boundary layer first becomes unstable on the NACA 64A010 airfoil can be made to jump from the trailing edge to the region near the leading edge. It may be of interest to note from figure 17(a) that the Reynolds number can be increased considerably and that the suction coefficient can be decreased appreciably without exposing much of the trailing surface to turbulent flow.

The curves of $R_{\delta}^*_{crit}$ and R_{δ}^* can be found at any Reynolds number, when they are known at one Reynolds number and one value of v_o/U_o , by noting that if $\frac{v_o}{U_o} \sqrt{R}$ does not vary with Reynolds number then the $R_{\delta}^*_{crit}$ curve is independent of Reynolds number and

$$\frac{R_{\delta}^*_{2}}{R_{\delta}^*_{1}} = \sqrt{\frac{R_2}{R_1}} \quad (1)$$

Thus, for a given distribution of $\frac{v_o}{U_o} \sqrt{R}$, which results in a fixed distribution of $R_{\delta}^*_{crit}$, the R_{δ}^* curve for the same distribution

of $\frac{v_o}{U_o} \sqrt{R}$ but some other R can be found by equation (1). At some R , R_{δ}^* will touch and yet not cross the $R_{\delta}^*_{crit}$ curve at only one point.

(See fig. 17.) This procedure results in one point on the curve of figure 16 which shows the variation of R with the minimum C_Q required to produce full-chord laminar stability. Other points on the curve of figure 16 may be found by application of the foregoing procedure to other choices of $\frac{v_o}{U_o} \sqrt{R}$ which result in other $R_{\delta}^*_{crit}$ distributions.

Because the first theoretical studies of the effects of suction on boundary-layer stability were made for the flow over a flat plate, it was thought of interest to include the curve for the flat plate in figure 16 wherein it is illustrated that no suction is required to keep the flow stable on a flat plate when the Reynolds number is sufficiently low. This result is in contrast to that for the airfoil which, because of the adverse pressure gradient over its rear portion, requires suction at all Reynolds numbers to maintain laminar flow to the trailing edge. Figure 16, however, indicates the rather surprising result that in order to keep full-chord laminar flow at large Reynolds numbers the NACA 64A010 airfoil requires smaller values of C_Q than are required for a flat plate. This outcome seems reasonable because, near the leading edge where both the flat plate and the airfoil become critical at high Reynolds numbers, the airfoil profits from the existence of a favorable pressure gradient which increases the critical boundary-layer Reynolds number and decreases the actual boundary-layer Reynolds number over that of the flat plate for the same free-stream Reynolds number.

Comparison between Theory and Experiment

The theoretical variations of R_{δ}^* , and $R_{\delta}^*_{crit}$, and $\frac{v_o}{U_o}$

with s/c cannot be compared with experiment because local inflow velocities and boundary-layer velocity profiles were not measured. The theoretical total-suction quantities can, however, be compared with the total suction quantities at the knees of the curves of wake-drag coefficient against suction-flow coefficient in figures 8(a) and 10(a).

The following table contains the results of the comparison between theory and experiment:

R	Minimum values of C_Q for laminar stability			
	Experimental		Theoretical	
	Uncompartmented	Compartmented	Neutral stability	Constant inflow
3.0×10^6	0.0028	0.0015	-----	0.00132
5.9	.0048	.0015	0.00056	.00096
7.6	-----	.0024	.00051	.00084
7.8	-----	.0034	.00051	.00083
9.0	.0100	-----	.00048	.00077

For the compartmented model, for which the inflow distribution was more nearly constant than for the uncompartmented model, the experimental value of C_Q at a Reynolds number of 3.0×10^6 is shown to agree very well with the theoretical value of C_Q for a constant chordwise inflow. The agreement between experiment and theory becomes less favorable at the higher Reynolds numbers because the minimum experimental C_Q for full-chord laminar flow depended on the effects of local outflow. The fact that the theoretical C_Q decreases with increasing Reynolds number indicates that it may be possible at least in the absence of roughness to maintain full-chord laminar flow with a small expenditure of power at larger Reynolds numbers if the experimental suction distribution is made to conform more nearly to that of the theoretical.

CONCLUDING REMARKS

Results have been presented of a two-dimensional wind-tunnel investigation of an NACA 64A010 airfoil with a porous surface of sintered bronze; related theoretical results also have been presented for comparison.

Application of area suction made possible the attainment of virtually full-chord laminar flow, at least for Reynolds numbers up to 7.8×10^6 , in spite of the fact that the airfoil surface was neither aerodynamically smooth nor fair. At a Reynolds number of 6.0×10^6 , the total-drag coefficient (wake drag plus the drag equivalent of the suction power required) was equal to 0.0028 as compared with a value of at least 0.0052 for the same model without area suction, that is, surface sealed.

Good agreement between experimental and theoretical suction quantities required for full-chord laminar flow was obtained at a Reynolds number of 3.0×10^6 , but not at the larger Reynolds numbers. The model underskin-throttling orifices could be designed to give a near-uniform chordwise inflow distribution only at free-stream Reynolds numbers below the design value, which for this model was about 6.0×10^6 . For this reason, a nonuniform inflow existed at the higher Reynolds numbers, thus excessive suction-flow rates (in poor agreement with theoretical results) were required to prevent boundary-layer transition caused by outflow of air through the airfoil surface. The excessive flows resulted in no decrease in total drag at Reynolds numbers greater than approximately 8.0×10^6 . The experimental results, however, indicated the possibility of extending low-drag characteristics to larger Reynolds numbers by means of an improved chordwise distribution of suction inflow.

Area suction appeared to decrease the angular spread of turbulence emanating from an individual surface disturbance.

Although area suction was able to overcome the destabilizing effects of an adverse pressure gradient such as occurs over the rear portion of an airfoil, area suction does not appear to stabilize the boundary layer completely for relatively large disturbances such as those which might be caused by protuberances that have a height comparable to the boundary-layer thickness. Further research is required to determine quantitatively the stability of suction-type profiles to finite disturbances.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., April 12, 1949

APPENDIX A

SINTERED-BRONZE SUCTION REQUIREMENTS FOR
THE CASE OF INCIPIENT LOCAL OUTFLOW

Several important conclusions may be drawn from a study of the conditions that cause local outflow through a porous sintered-bronze sheet installed on an airfoil as a boundary-layer suction surface. Outflow occurs through any point on the skin where the local static pressure on the inside of the skin is greater than the local external static pressure despite the existence of a difference in pressures at all other points such as to produce inflow. An internal pressure just low enough to prevent outflow at some critical point produces an average value of area suction-flow coefficient which depends on the porosity characteristics of the material.

For a given type of sintered bronze, the velocity into the surface varies directly as the pressure drop across the surface and inversely as the thickness of the sheet and the absolute viscosity of the fluid; thus,

$$v_o = -\frac{c_{v_o} \Delta p}{\mu t} \quad (A1)$$

A dimensional analysis will show that the factor c_{v_o} has the dimensions

of $(\text{length})^2$. This length is related to the effective diameter of the passages leading through the material. So long as the flow is of the purely viscous type, the value of c_{v_o} for a specific piece of porous

material may be expected to be independent of the physical characteristics of the fluid passing through the material, that is, the viscosity and density.

Inasmuch as the suction-drag coefficient increases directly as the suction-flow coefficient C_Q (see appendix B), it is of interest to note the manner in which the porosity relation, equation (A1), affects the minimum C_Q necessary to prevent outflow. The average area suction-flow coefficient for both sides of a two-dimensional airfoil may be written as

$$C_Q = \frac{Q}{U_{ocb} b} = \frac{-\oint b v_o ds}{U_{ocb} b} \quad (A2)$$

where the quantity of suction air is obtained by integrating the inflow velocity v_o over both upper and lower surfaces as indicated by the line integral sign. The inflow velocity given by equation (A1) may be rewritten as

$$v_o = -\left(\frac{c_{v_o} q_o}{\mu t}\right) \left[\left(\frac{H_o - H_1}{q_o}\right) - \left(\frac{H_o - p}{q_o}\right) \right] \quad (A3)$$

where H_1 is equal to the internal static pressure because the internal velocity, and therefore the dynamic pressure, is extremely low. The two relations in equation (A3), $\frac{H_o - H_1}{q_o}$ and $\frac{H_o - p}{q_o}$, are the suction pressure-loss coefficient and the external airfoil pressure coefficient, respectively. The inflow velocity at any point is now

$$v_o = -\frac{c_{v_o} q_o}{\mu t} (C_P - S)$$

or

$$\frac{v_o}{U_o} = -\frac{c_{v_o}}{2ct} R (C_P - S) \quad (A4)$$

The suction-flow coefficient for the whole wing can now be written as

$$C_Q = -\frac{c_{v_o} R}{2ct} \oint (C_P - S) d\frac{s}{c} \quad (A5)$$

It may be seen by equation (A5) that, if conditions of airfoil pressure coefficient and suction pressure-loss coefficient remain fixed for a given porous-skin model wherein c_{v_o} , t , and c are fixed, the value

of C_Q to be associated with a given value of $\oint (C_P - S) d\frac{S}{c}$ will vary linearly with R . Thus, for the outflow value of the integral where C_P equals S at some point on the airfoil and is higher at all other points, the value of C_Q corresponding to outflow will increase linearly with increasing R , a result approximately in agreement with experimental results.

In order to have like test conditions for like Reynolds number as ρ , U_0 , c , and μ are varied, it is necessary that c_{v_0}/t vary directly with c . When models of different chords are geometrically similar to the extent that t is proportional to c , then c_{v_0} must vary directly as c^2 . This result would be expected since it means that the effective diameter of the passage must vary directly as the chord; that is, the geometrical similarity must include the detailed geometry of the structure of the porous material, as well as the over-all dimensions of the model.

For like airfoils of different chords covered with the same porous material, equation (A4) indicates that the inflow distribution at any chordwise position is unchanged if R is proportional to c , that is, if U_0/v is a constant. Thus, if the same airfoil profile were used throughout the span of a tapered wing and the wing were entirely covered with the same porous material, the inflow distribution would be similar for all sections of the tapered wing for the convenient condition of a constant suction pressure within the wing.

Compartmentation of an area-suction model can be used as a method for improving the chordwise inflow distribution so that excessive suction flows will not occur at any point, but, if this method is used, each compartment must be considered as a source of outflow. The flow removed through each compartment can be decreased by decreasing the pressure drop across the porous surface with a throttling device; and thus the effective C_P based on the static pressure in the compartment becomes less for no outflow than the C_P that would be required at the point of maximum S on the airfoil. (See fig. 2.) The net result of compartmenting the whole airfoil is that for no outflow the sum of the incremental values of C_Q for each compartment will be less than the minimum C_Q required for no outflow for the uncompartmented model and, furthermore, the greater the number of compartments, the greater the decrease in the value of total C_Q for incipient outflow. The end point of more and more compartments is that the chordwise inflow distribution can be set to any value desired. The greatest difficulty in compartmenting is experienced at and near the nose where even very small compartments must combat a very high chordwise change in pressure drop and thus of inflow.

distribution because of large variations in the external pressure. Inasmuch as extreme compartmentation may result in an immense construction problem, it may be more desirable to provide a skin which has a chordwise variation of porosity that will produce the desired inflow distribution. Such a skin could be obtained by a chordwise variation of either the thickness or the density of the material.

APPENDIX B

DETERMINATION OF SUCTION-DRAG COEFFICIENT

If it is assumed that the suction air is pumped back to free-stream total pressure by a blower and duct system which together have an efficiency of η_s , then the power required may be written as

$$P = \frac{Q(H_0 - H_1)}{\eta_s}$$

where H_1 is the average total pressure of the suction as measured at a point under the surface of the wing and H_0 is the free-stream total pressure.

If the flow quantity is expressed as the suction-flow coefficient

$$C_Q = \frac{Q}{U_0 bc}$$

and the total pressure defect is expressed as a pressure-loss coefficient

$$C_P = \frac{H_0 - H_1}{q_0}$$

then the power may be written as

$$P = \frac{C_Q U_0 bc C_P q_0}{\eta_b} \quad (B1)$$

If this amount of power were to be supplied by the airplane propulsive system of efficiency η_p , then the equivalent drag to be associated with this power could be written as

$$D = \frac{P \eta_p}{U_0}$$

or

$$c_{d_s} b c_{q_0} = \frac{P \eta_p}{U_o} \quad (B2)$$

where the equivalent drag is expressed in terms of a suction-drag coefficient based on the area of the wing.

Equations (B1) and (B2) permit the suction-drag coefficient to be expressed as

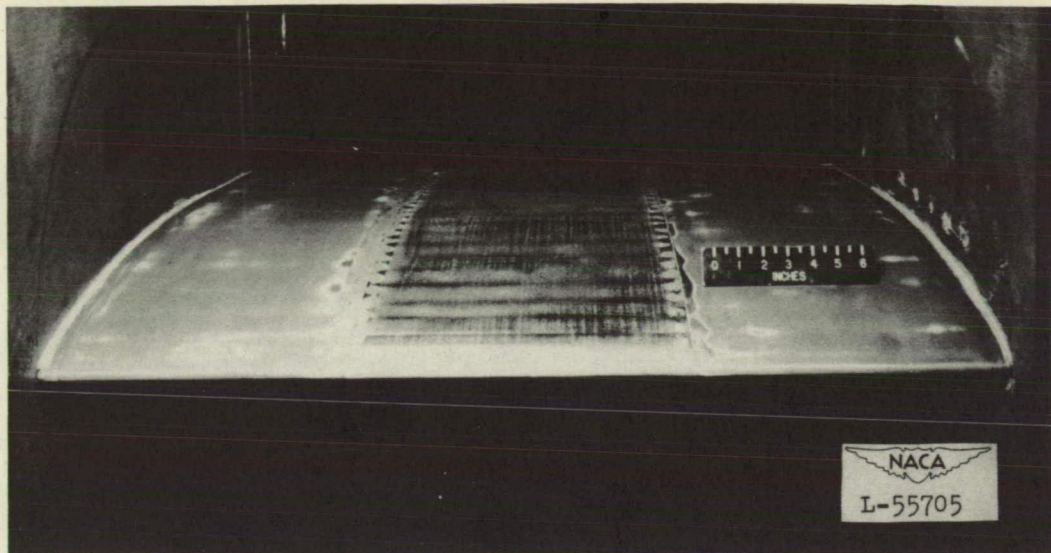
$$c_{d_s} = C_Q C_P \frac{\eta_p}{\eta_s}$$

On the condition that the blower system operates as efficiently as the propulsive system, the suction-drag coefficient reduces to

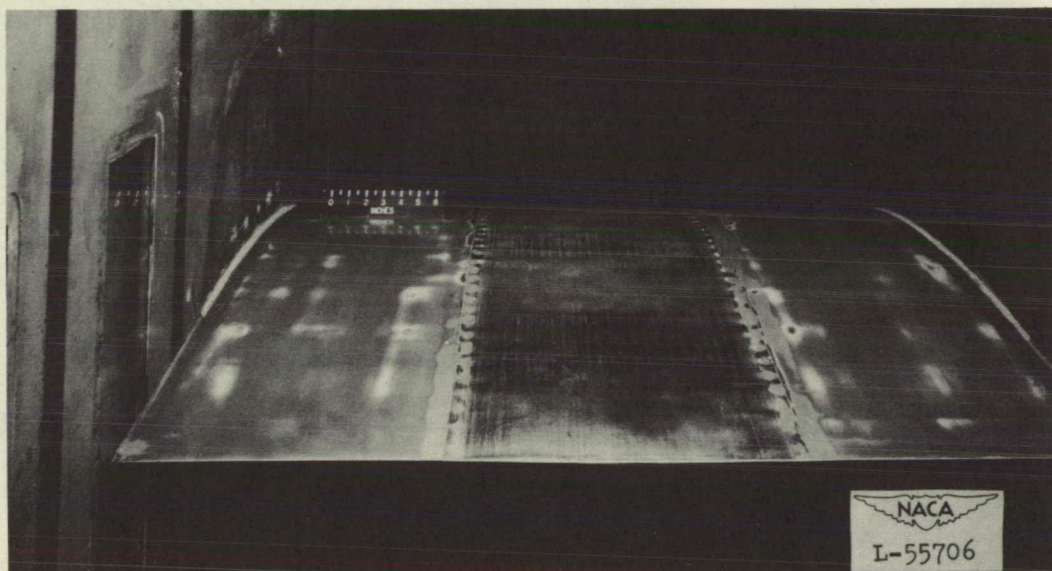
$$c_{d_s} = C_Q C_P \quad (B3)$$

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(a) Leading edge.



(b) Trailing edge.

Figure 1.— NACA 64A010 airfoil model with porous sintered-bronze surface mounted for area-suction studies in Langley two-dimensional low-turbulence pressure tunnel.

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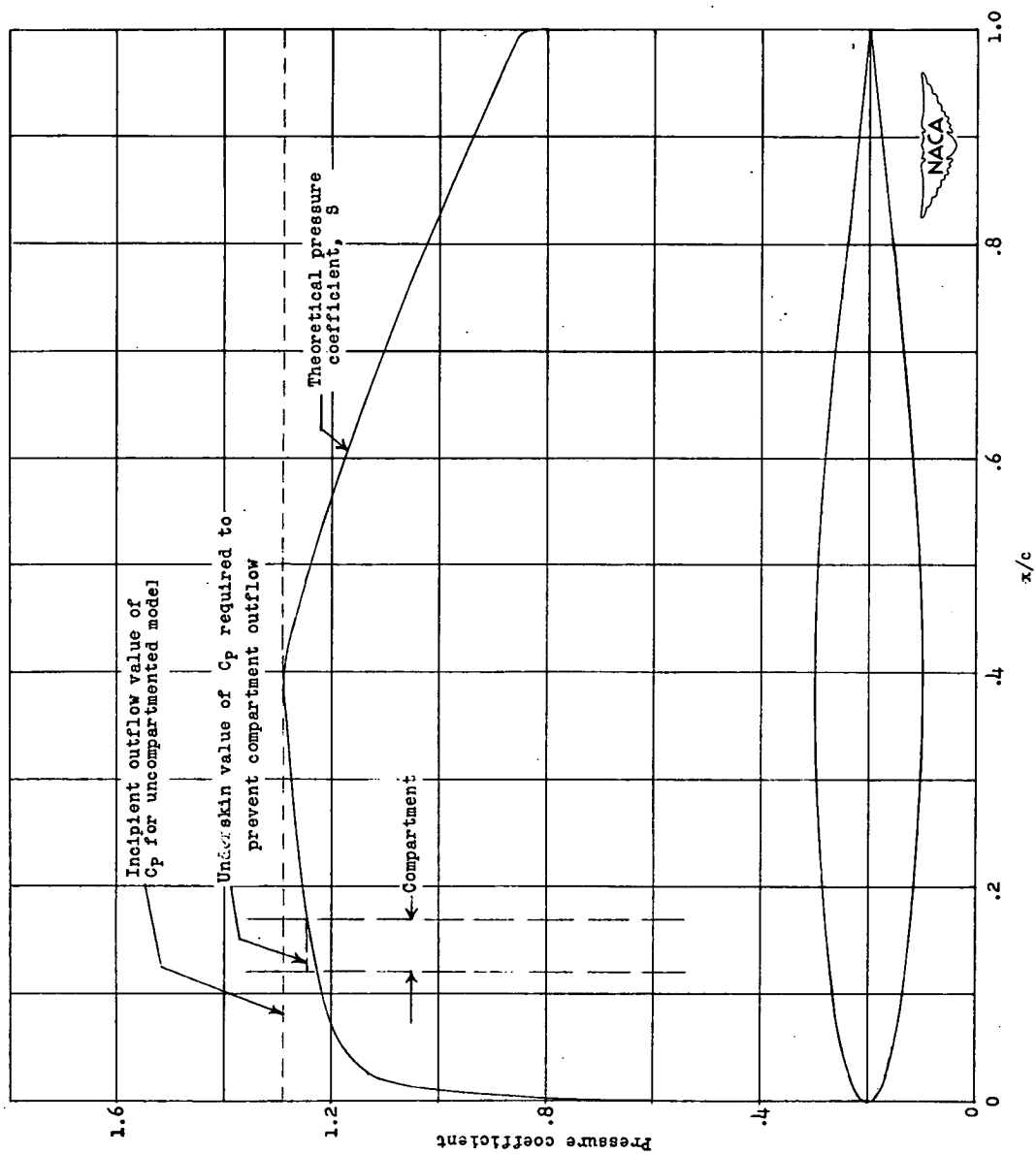
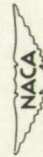
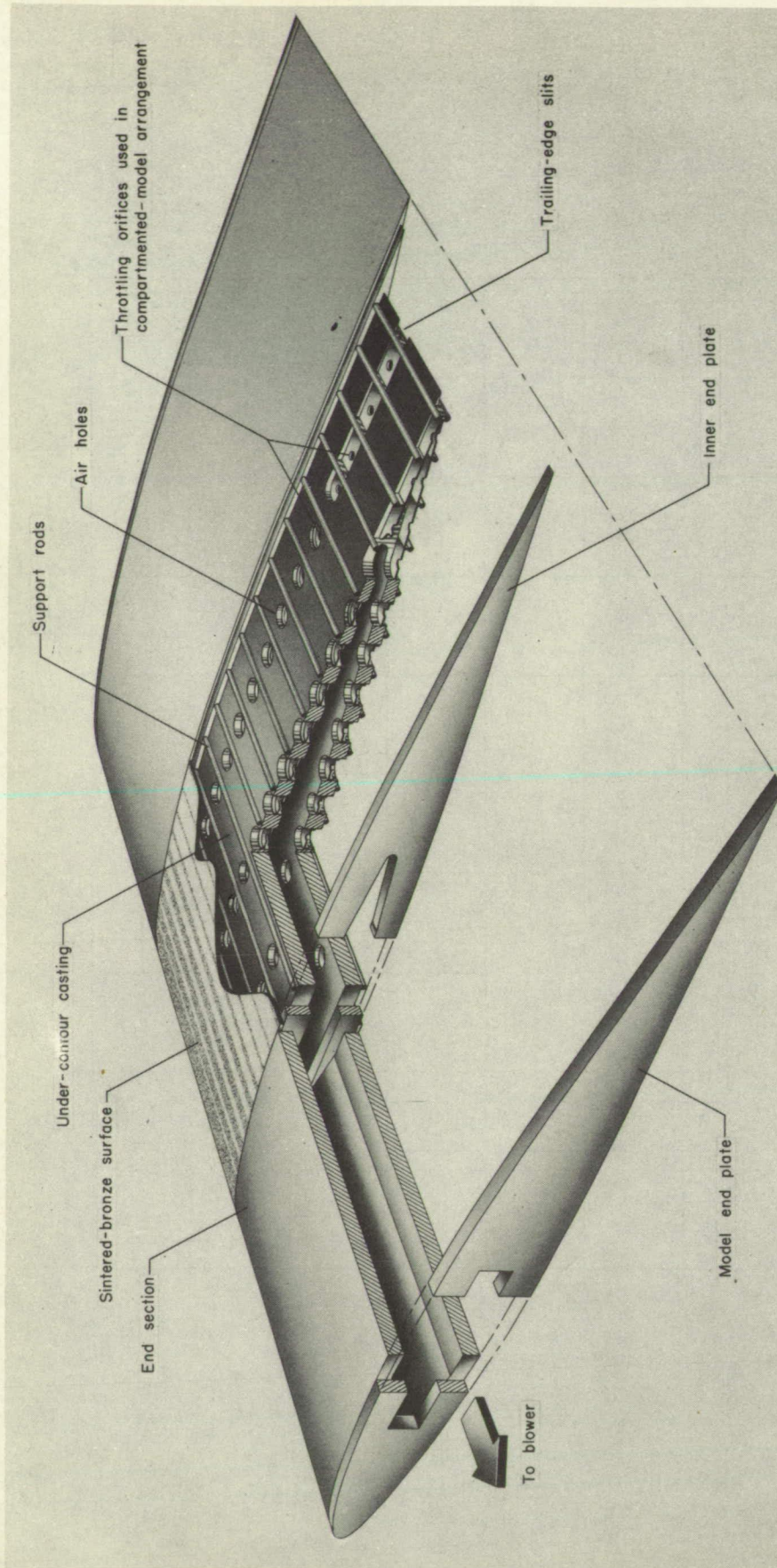


Figure 2.- External-pressure and suction-pressure distributions for porous bronze NACA 64A010 airfoil model. $\alpha_0 = 0^\circ$.



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Figure 3.— Construction of porous bronze NACA 64A010 airfoil model.

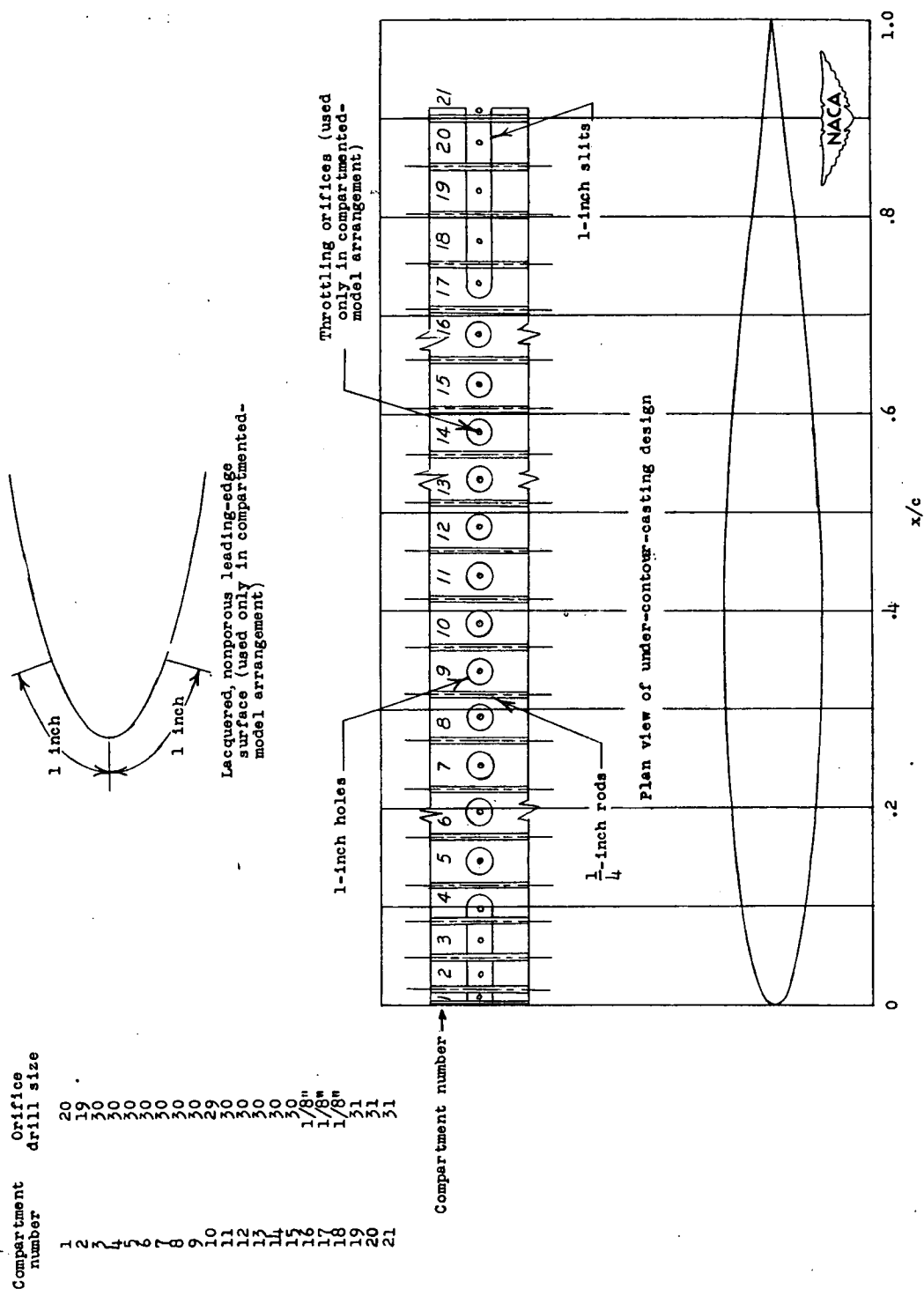


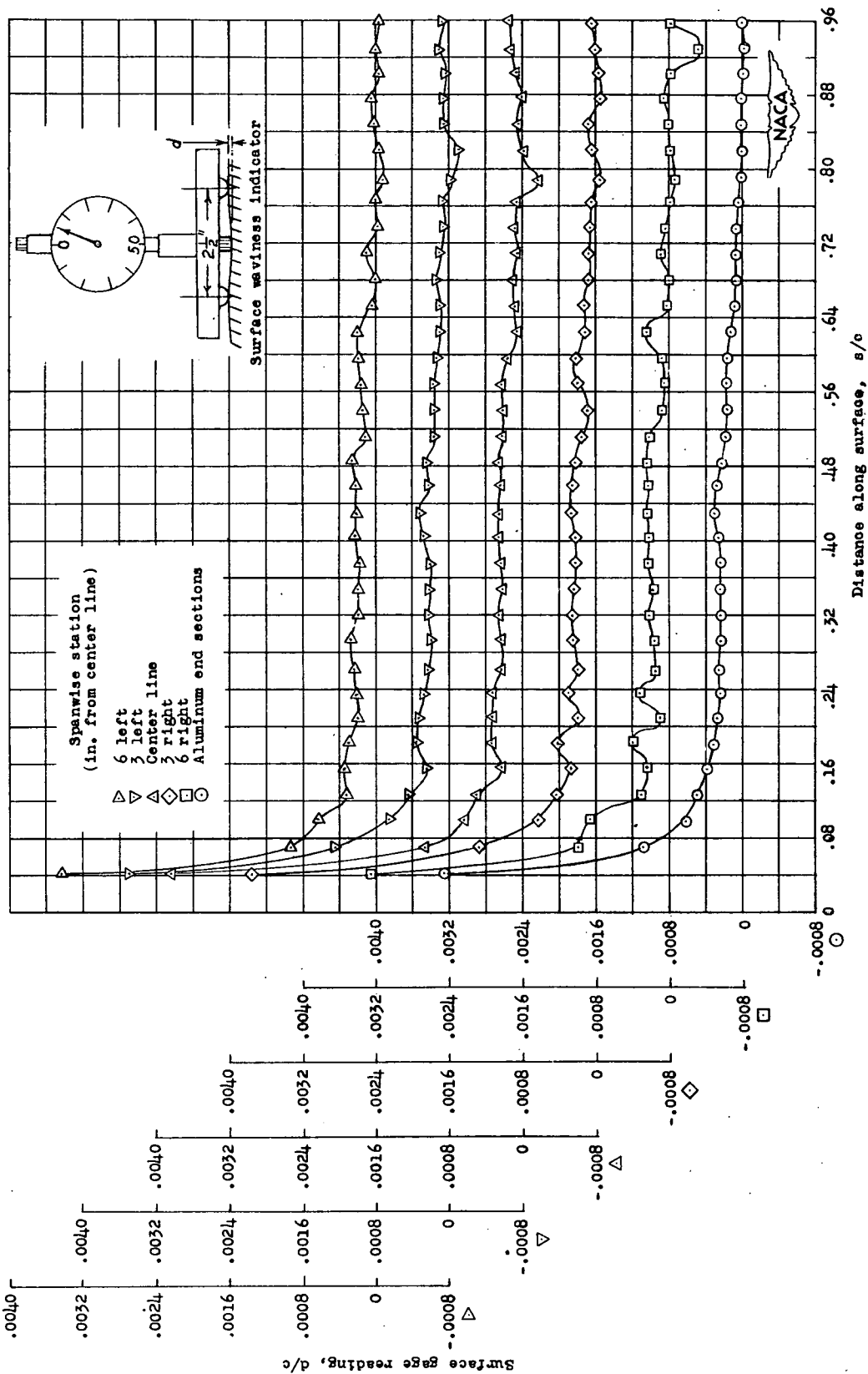
Figure 4.- Chordwise locations of support rods and throttling orifices of porous bronze NACA 64A010 airfoil model.

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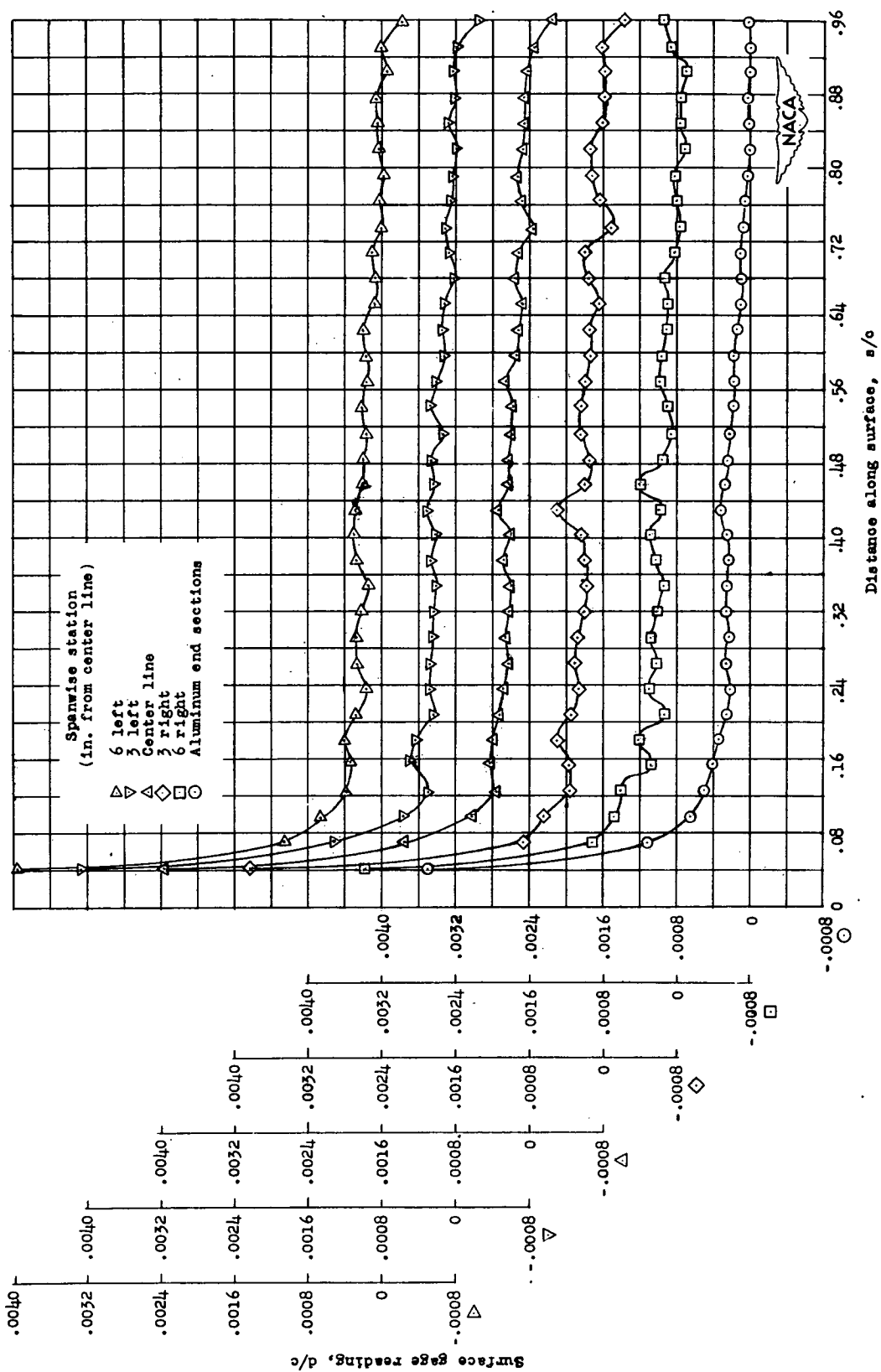


Figure 5.— NACA 64A010 airfoil model with porous sintered-bronze surface removed.



(a) Upper surface.

Figure 6.— Chordwise surface waviness survey for various spanwise positions across porous bronze NACA 64A010 airfoil model.

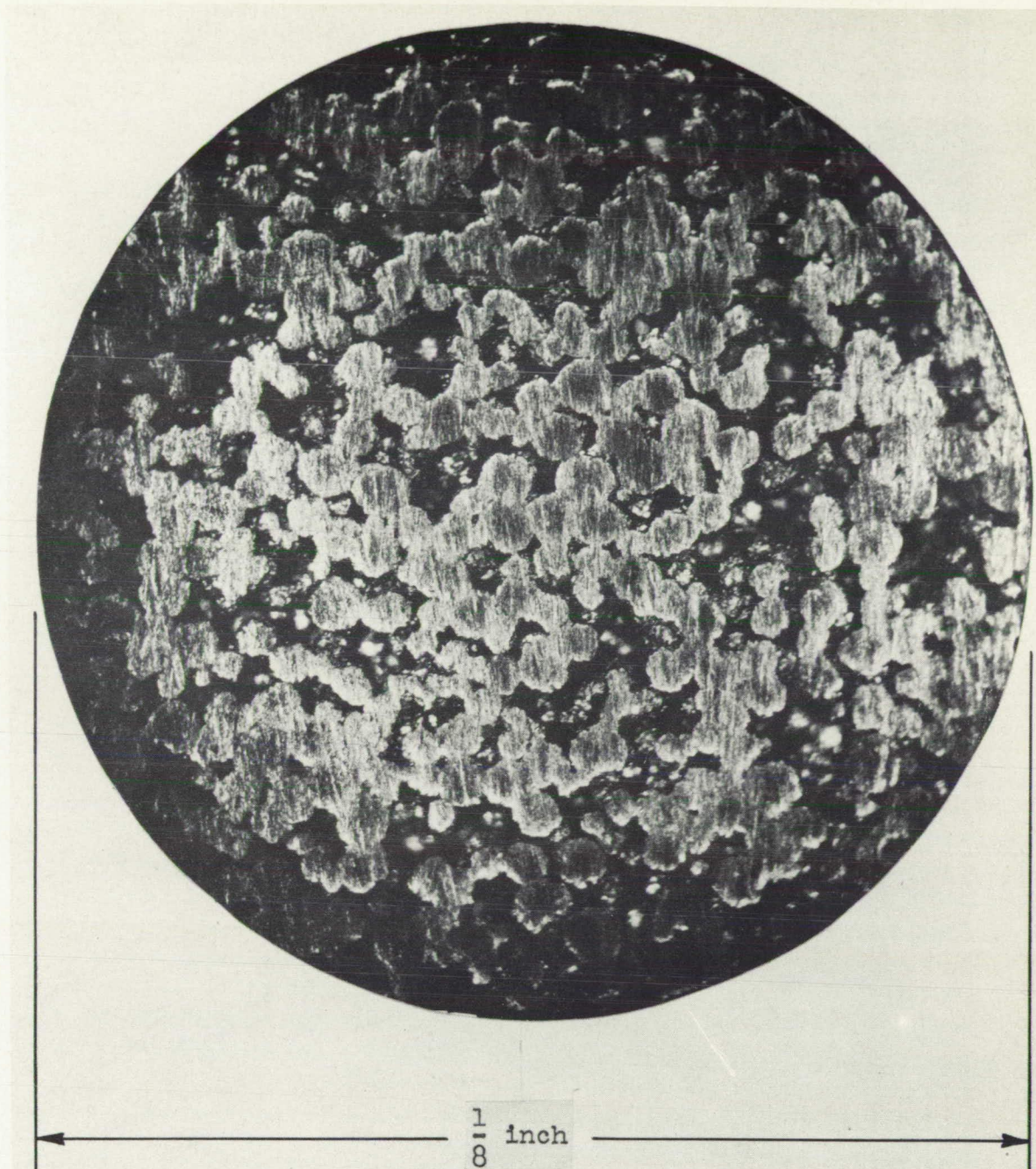


(b) Lower surface.

Figure 6.— Concluded.

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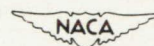
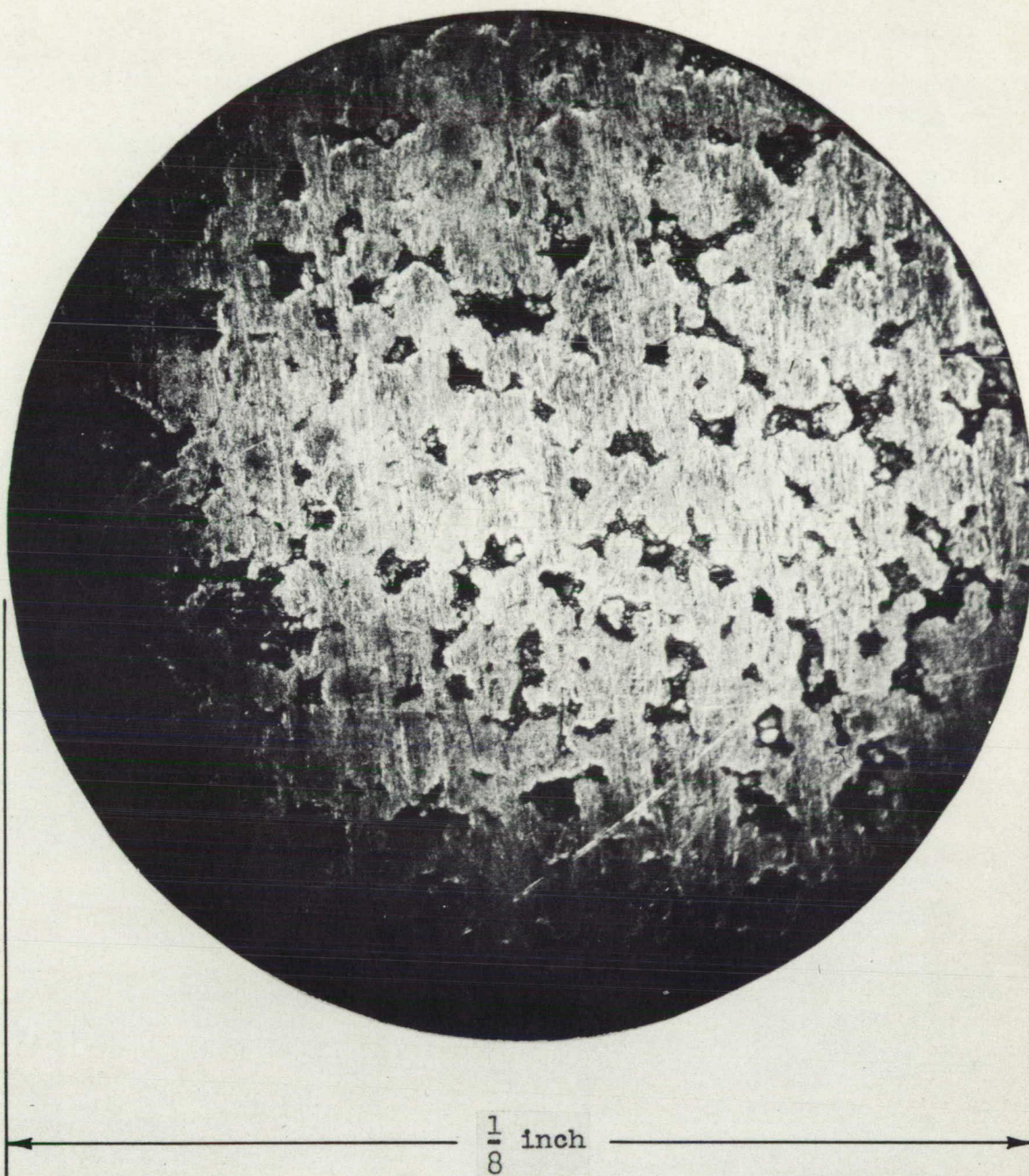
NACA
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(a) Representative of approximately 80 percent of total area.

Figure 7.— Photomicrographs of sanded sintered-bronze surface as tested.

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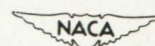
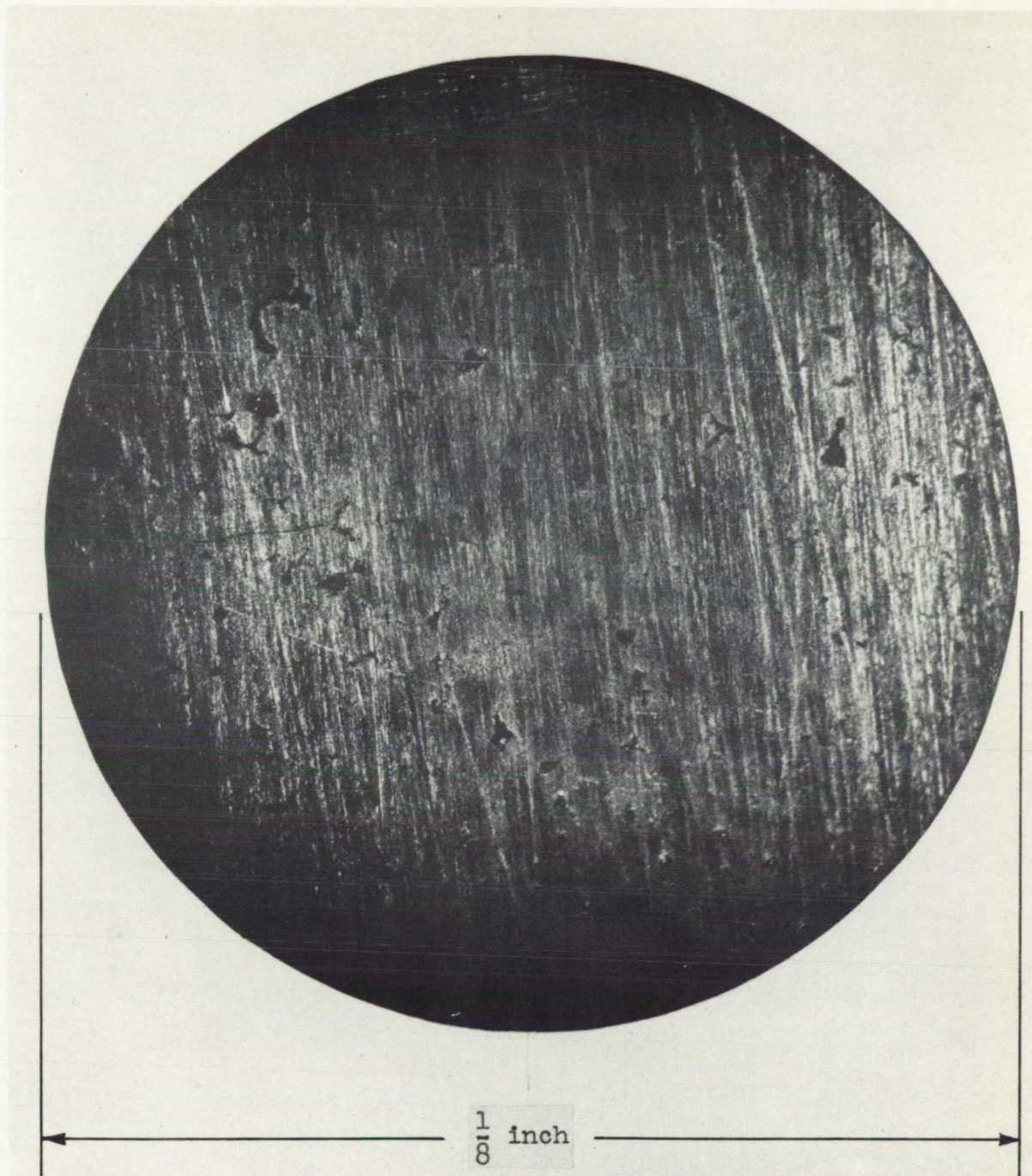
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(b) Representative of approximately 19 percent of total area.

Figure 7.- Continued.

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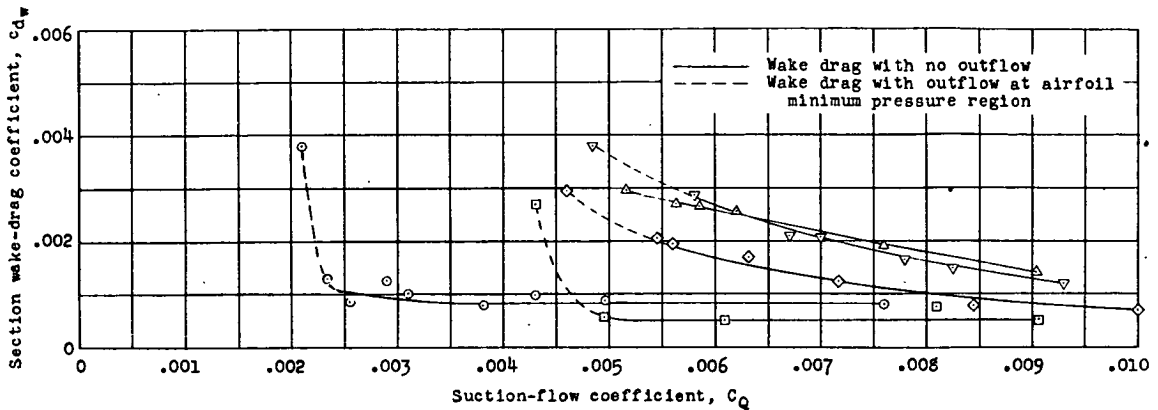
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(c) Representative of approximately 1 percent of total area.

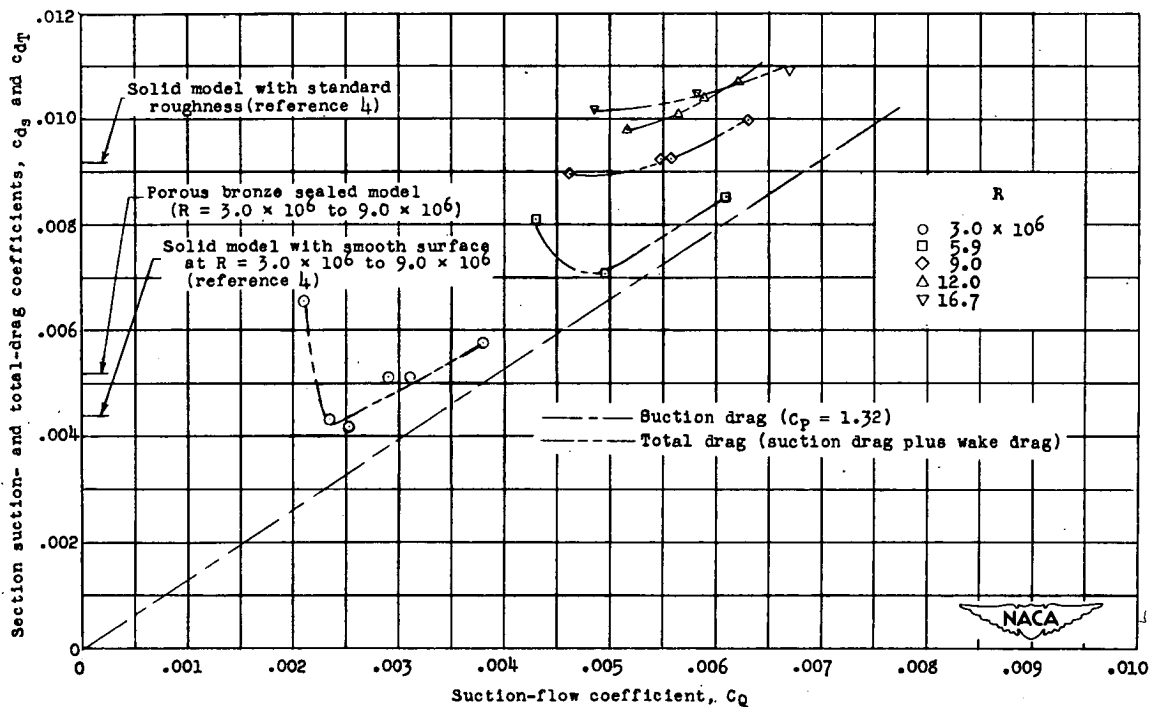
Figure 7.— Concluded.

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(a) Wake drag (measured at model center line).



(b) Suction and total drag.

Figure 8.— Variation of section drag coefficients with suction-flow coefficient for porous bronze NACA 64A010 airfoil model.

$$\frac{c_{v0}}{c_t} = 7.2 \times 10^{-9}; \alpha_0 = 0^\circ; \text{uncompartmented model.}$$

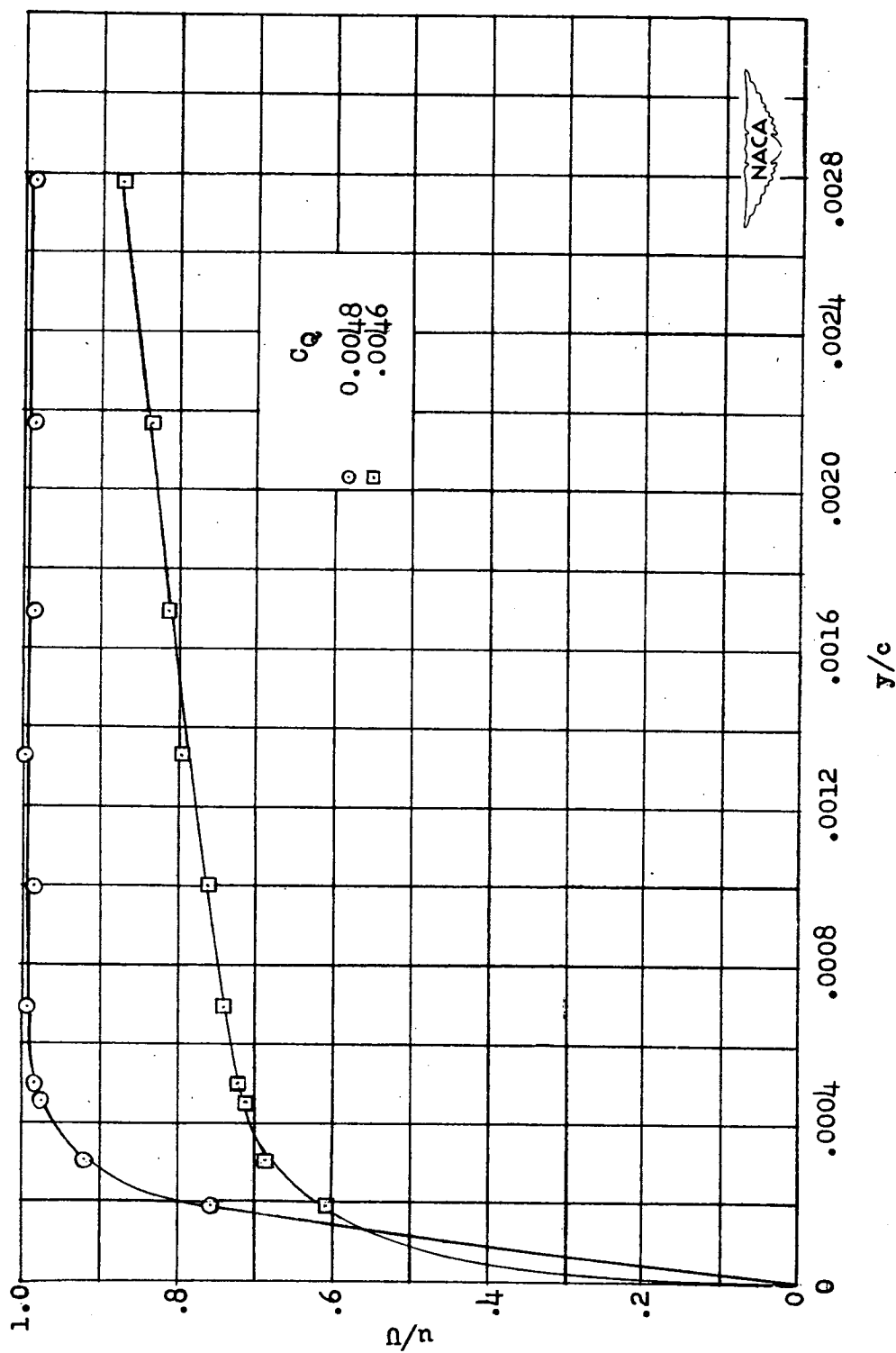
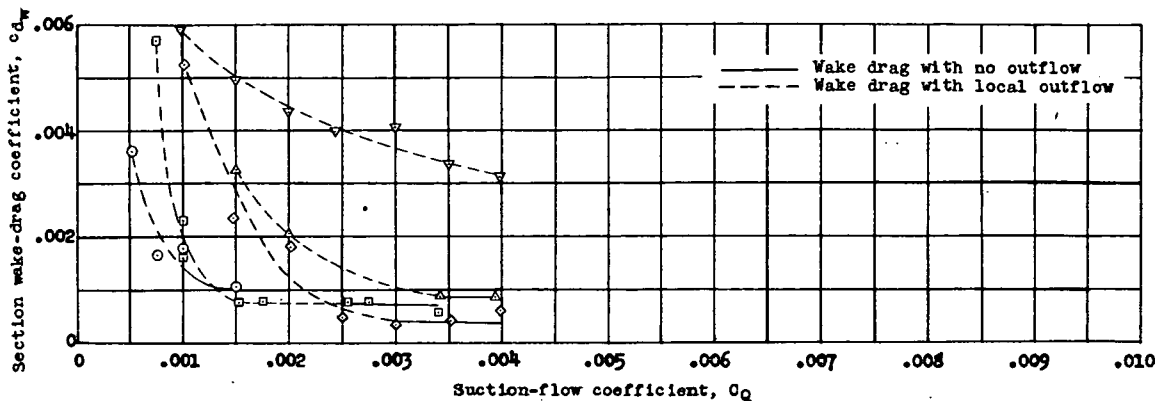
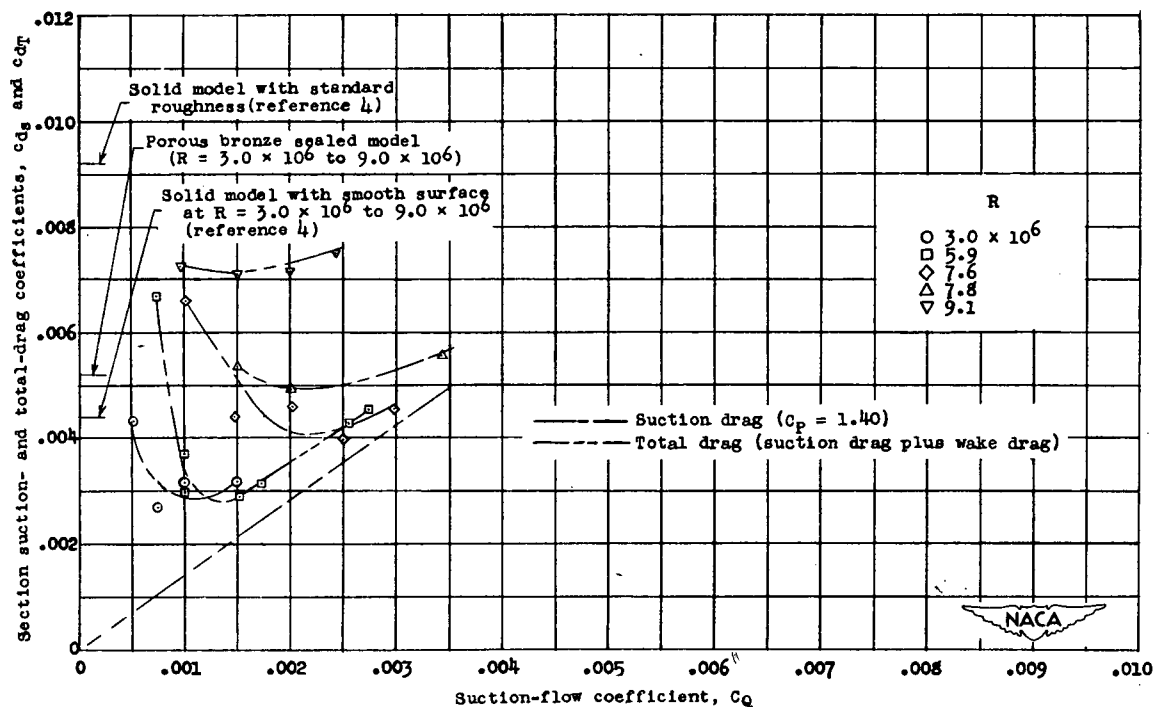


Figure 9.—Boundary-layer surveys for two values of suction-flow coefficient at station 0.83c on upper surface of porous bronze NACA 64A010 airfoil model. Uncompartmented model; $R = 6.0 \times 10^6$; $\alpha_0 = 0^\circ$.



(a) Wake drag (measured at model center line).



(b) Suction and total drag.

Figure 10.— Variation of section drag coefficients with suction-flow coefficients for porous bronze NACA 64A010 airfoil model.

$$\frac{c_{v0}}{ct} = 7.2 \times 10^{-9}; \alpha_0 = 0^\circ; \text{compartmented model.}$$

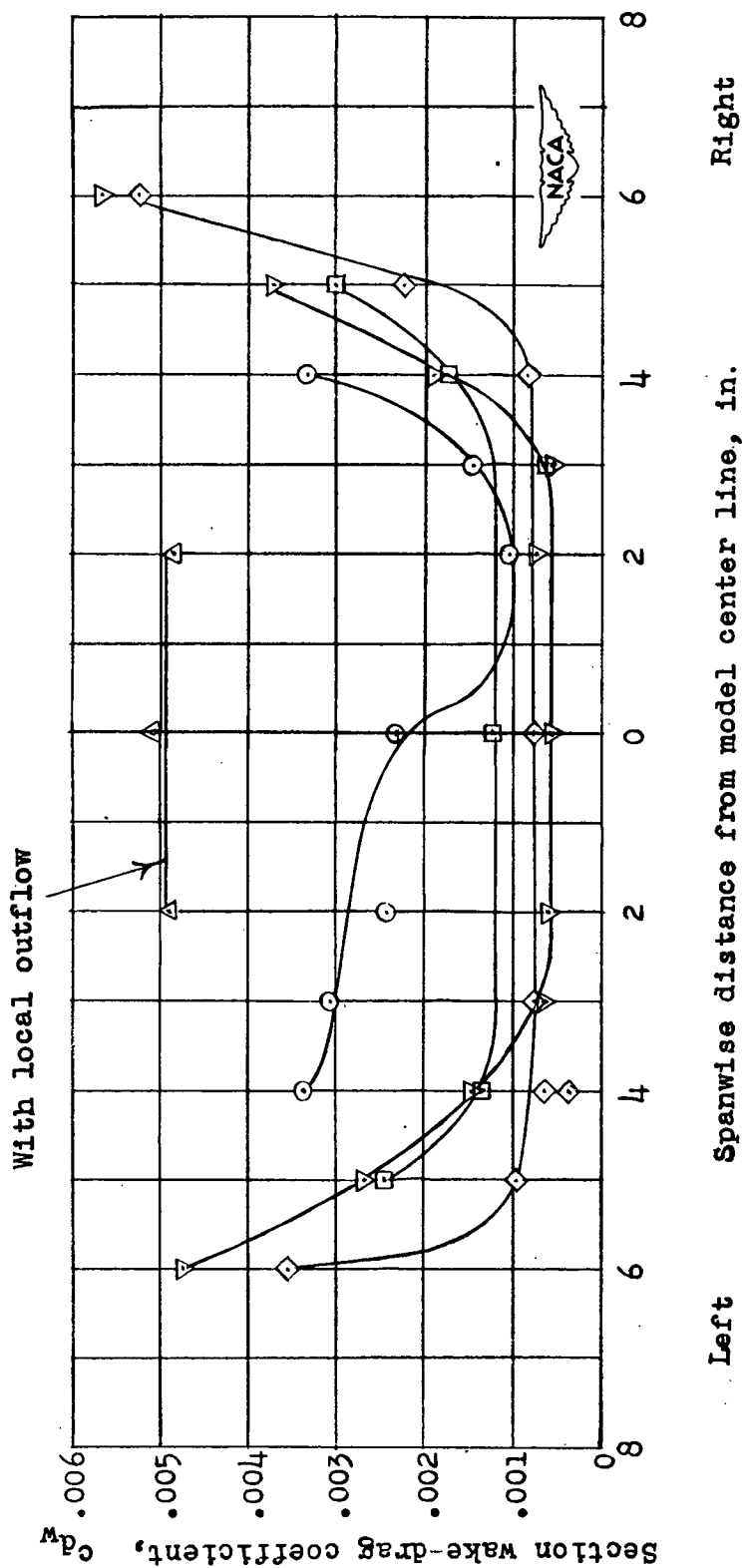


Figure 11.— Spanwise variation of section profile-drag coefficient with different suction-flow coefficients for porous bronze NACA 64A010 airfoil model for two Reynolds numbers. Uncompartmented model; $\alpha_0 = 0^\circ$.

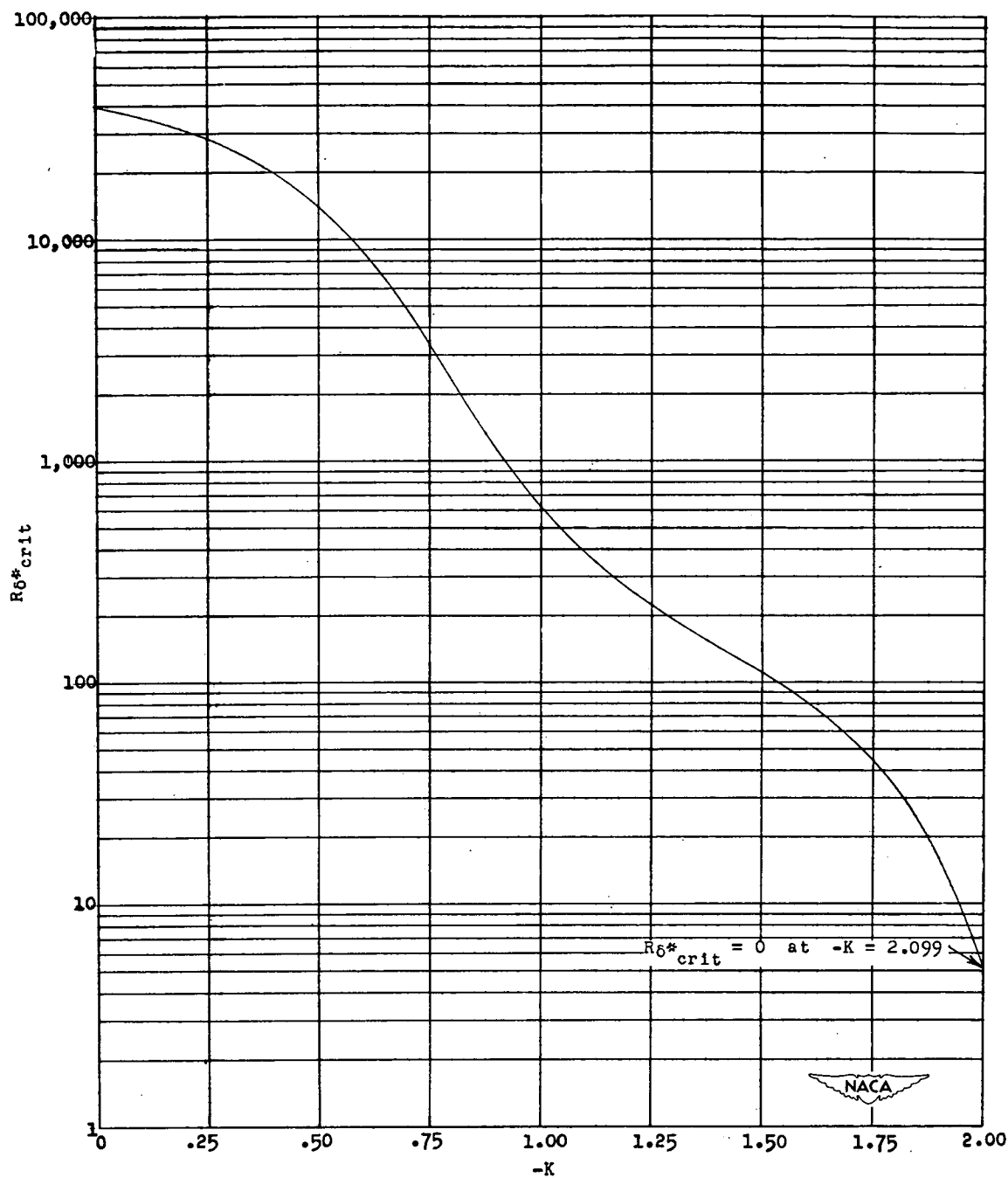


Figure 12.— Theoretical variation of critical boundary-layer Reynolds number with boundary-layer shape parameter.

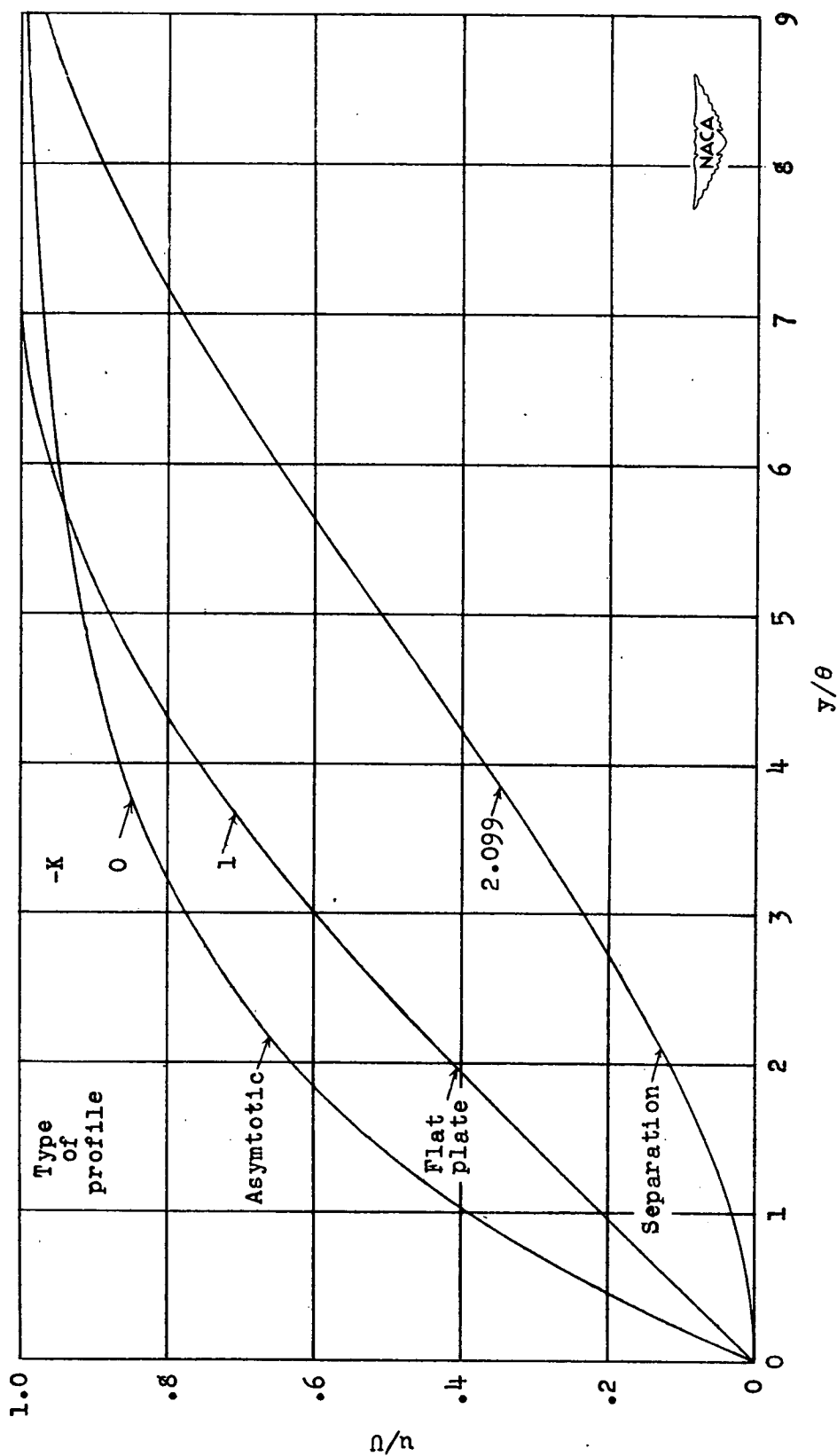


Figure 13.— Several boundary-layer profiles for values of shape parameter K as calculated by Schlichting.

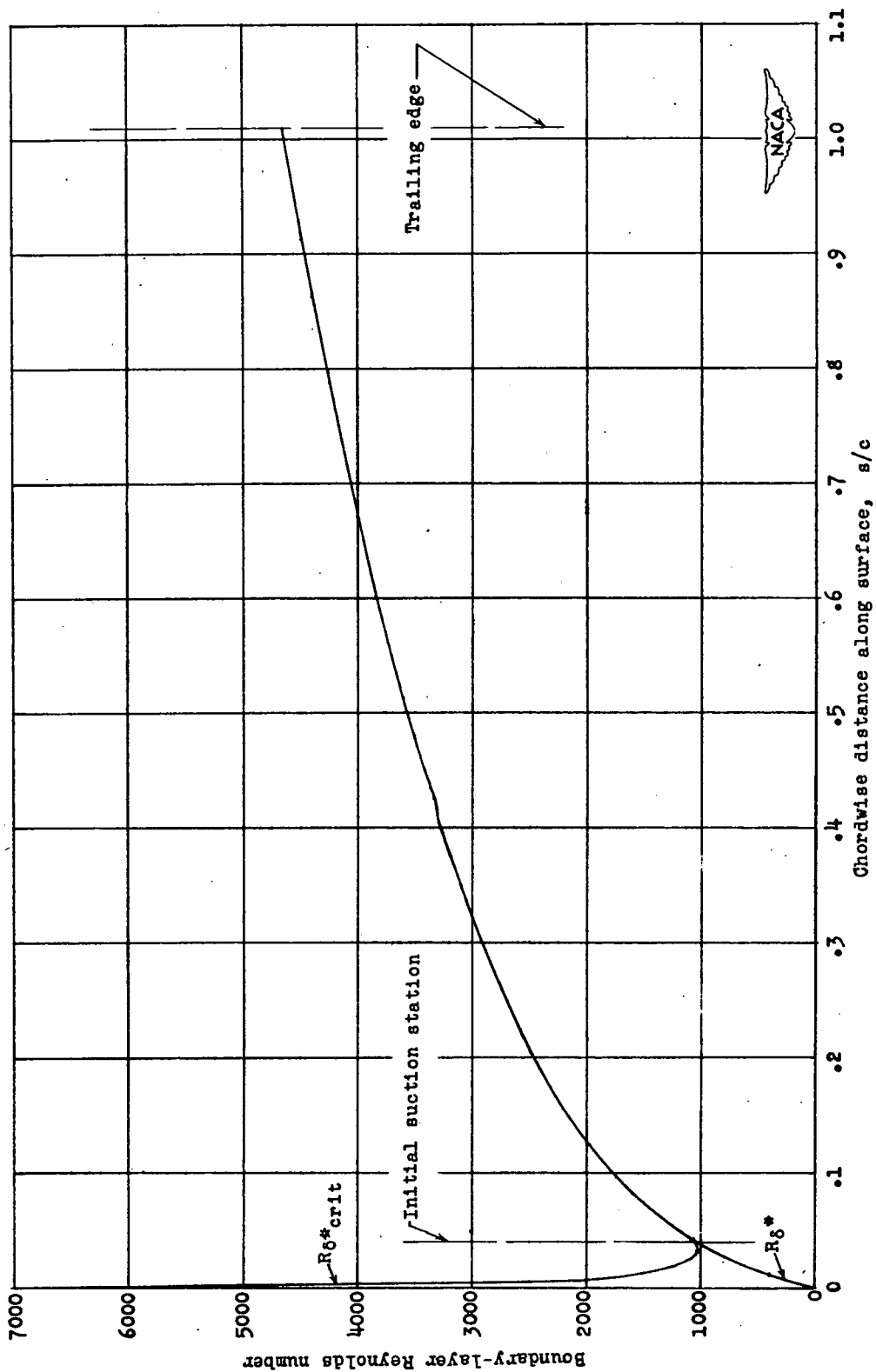


Figure 14.— Theoretical chordwise variation of boundary-layer Reynolds number on the NACA 64A010

airfoil for $R_{\delta^*} = R_{\delta^*crit}$; $R = 15.0 \times 10^6$; $C_Q = 0.000405$; $\alpha_0 = 0^\circ$.

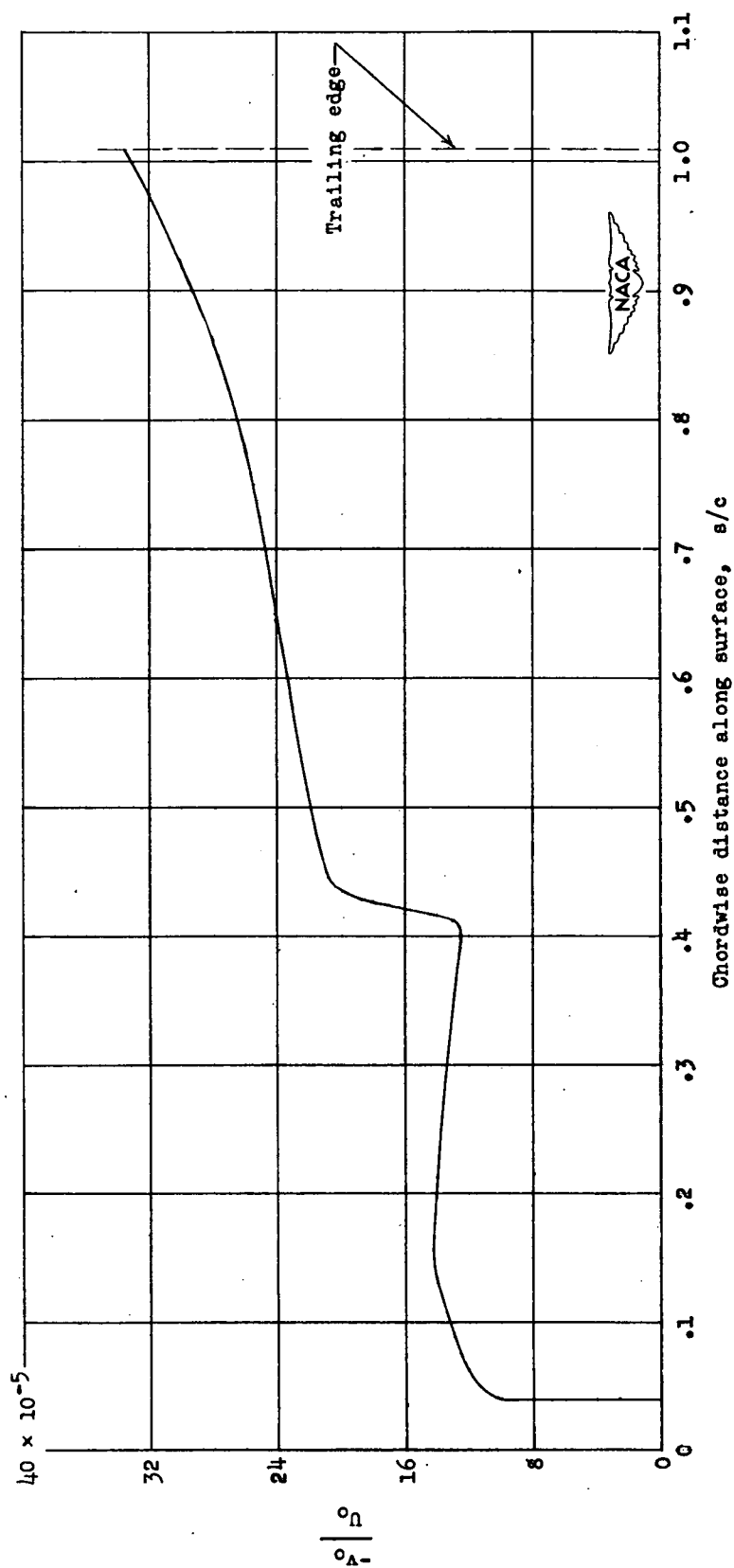


Figure 15.— Theoretical chordwise variation of minimum suction velocity ratio required to produce neutral stability at all points along the chord of the NACA 64A010 airfoil. $R = 15.0 \times 10^6$; $\alpha_0 = 0^\circ$; $C_Q = 0.000405$.

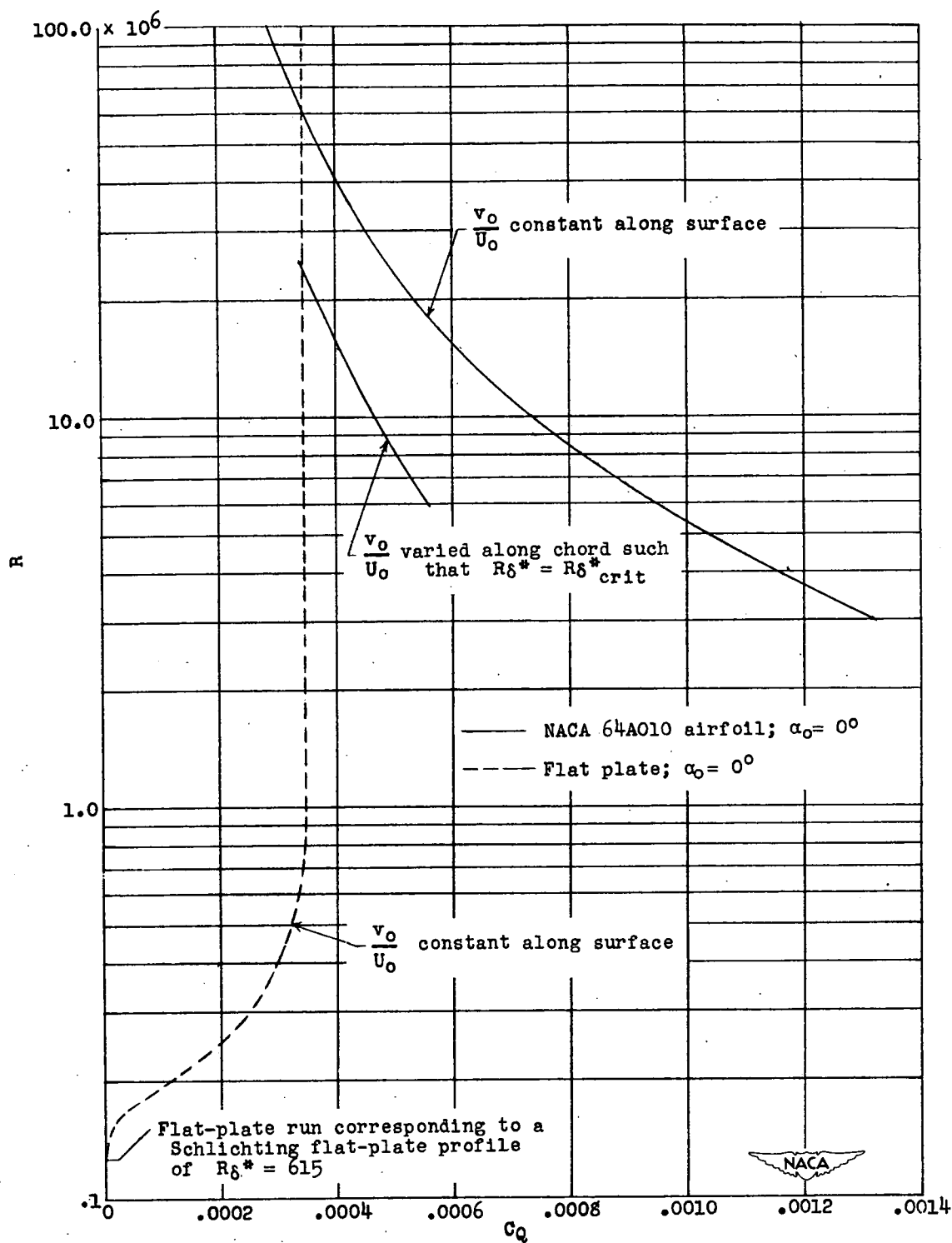
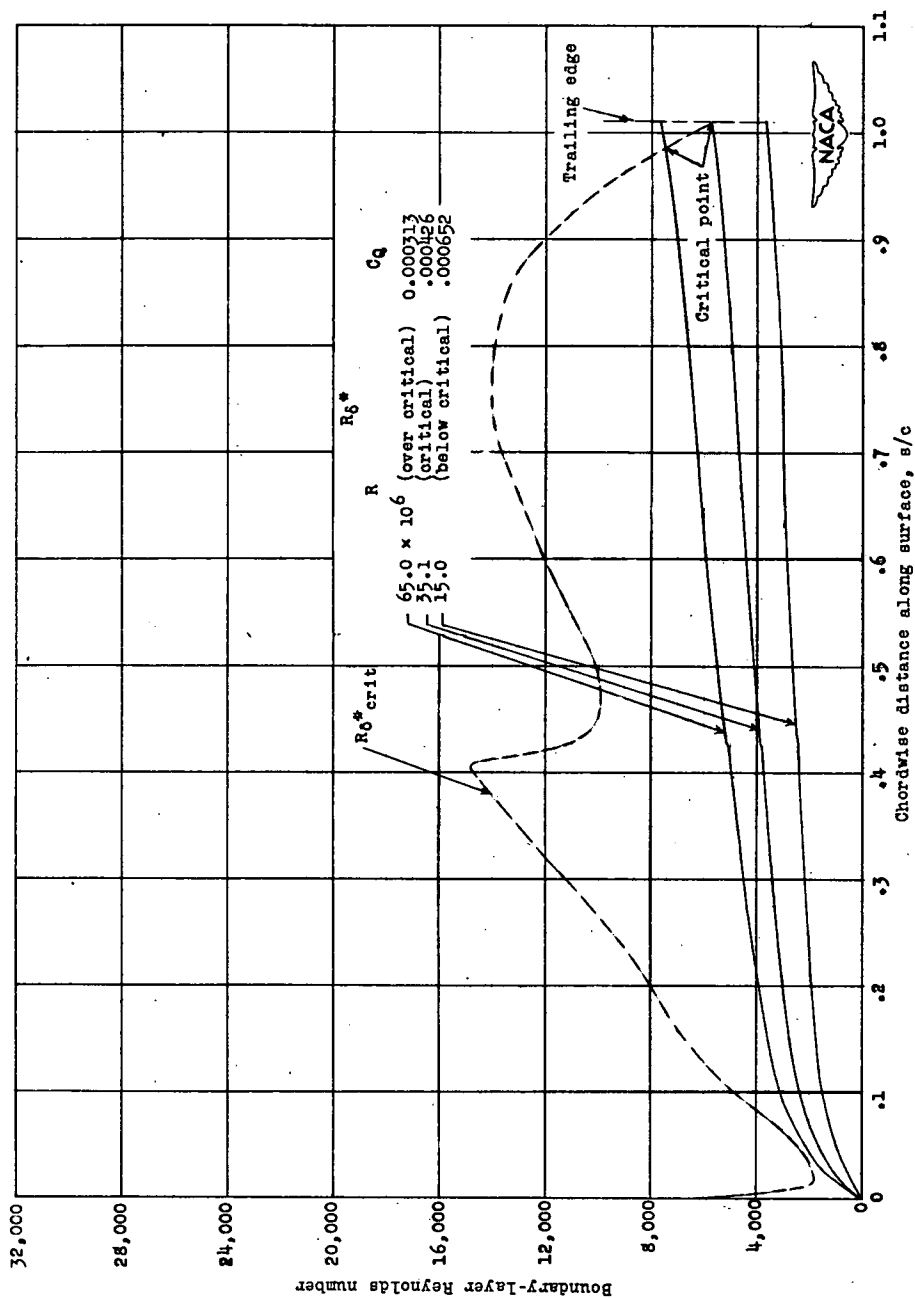
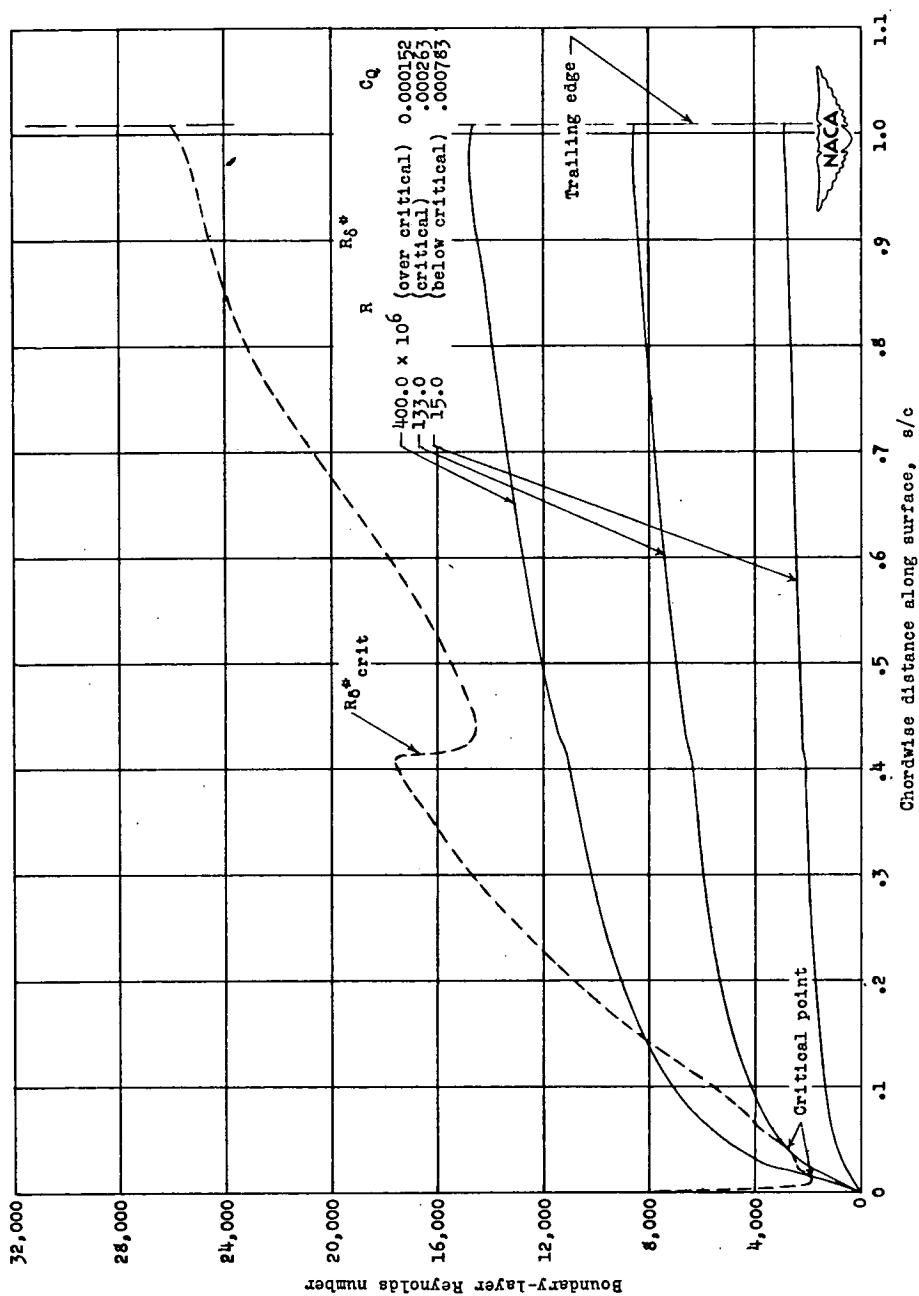


Figure 16.— Theoretical variation of free-stream Reynolds number with minimum suction-flow coefficient required to produce full-chord laminar stability.



(a) Critical point near trailing edge; $\frac{-V_0}{U_0} \sqrt{R} = 1.25$.

Figure 17.-- Theoretical chordwise variation of boundary-layer Reynolds number and critical boundary-layer Reynolds number for the NACA 64A010 airfoil at three free-stream Reynolds numbers for constant chordwise inflow velocity. $\alpha_0 = 0^\circ$.



(b) Critical point near leading edge; $\frac{v_0}{U_0} \sqrt{R} = 1.50$.

Figure 17.— Concluded.